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THESIS

AN ACTIVITY-BASED NON-LINEAR REGRESSION MODEL OF SOPITE SYNDROME AND ITS EFFECTS ON CREW PERFORMANCE IN HIGH-SPEED VESSEL OPERATIONS

by

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March 2009

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13. ABSTRACT (maximum 200 words)

The Navy's future use of shallow-draft high-speed vessels has provoked questions regarding the effects of resulting ship motion on crews' performance. Sopite syndrome, a commonly overlooked subset of motion sickness, is responsible for lethargy, fatigue, drowsiness, difficulty concentrating and numerous other performance-diminishing symptoms in shipboard crewmembers who appear to be adapted to vessel motion (Graybiel & Knepton, 1976). Since its discovery in 1976, no physically measurable parameter to quantify Sopite syndrome and its effect on performance has been established. Recent efforts to develop high-speed shallow-draft vessels coupled with increased automation and reduced manning place a premium on every crewmember. The manning modifications make it more important than ever to ensure that personnel readiness and performance degradation are accounted for in manning model calculations. This study quantifies Sopite syndrome by using non-linear regression to model activity as a function of time underway and linear regression to model performance. Performance is modeled using the concept of daily activity levels concurrently with ship's motion data, individual demographics and motion sickness questionnaires as input parameters. It was found that over an eight-day underway period, performance on a three-minute manual dexterity task degraded by 2 to 3 percent due to Sopite syndrome.

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ABSTRACT

The Navy's future use of shallow-draft high-speed vessels has provoked questions regarding the effects of resulting ship motion on crews' performance. Sopite syndrome, a commonly overlooked subset of motion sickness, is responsible for lethargy, fatigue, drowsiness, difficulty concentrating and numerous other performance-diminishing symptoms in shipboard crewmembers who appear to be adapted to vessel motion. Since its discovery in 1976, no physically measurable parameter to quantify Sopite syndrome and its effect on performance has been established. Recent efforts to develop high-speed shallow-draft vessels coupled with increased automation and reduced manning place a premium on every crewmember. The manning modifications make it more important than ever to ensure that personnel readiness and performance degradation are accounted for in manning model calculations. This study quantifies Sopite syndrome by using non-linear regression to model activity as a function of time underway and linear regression to model performance. Performance is modeled using the concept of daily activity levels concurrently with ship's motion data, individual demographics and motion sickness questionnaires as input parameters. It was found that over an eight-day underway period, performance on a three-minute manual dexterity task degraded by two to three percent due to Sopite syndrome.

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EXECUTIVE SUMMARY

The Navy's future use of shallow-draft high-speed vessels has provoked questions regarding the effects of resulting ship motion on crew performance. Sopite syndrome, a commonly overlooked subset of motion sickness, is responsible for lethargy, fatigue, drowsiness, difficulty concentrating and numerous other performance diminishing symptoms in shipboard crewmembers that appear to be seemingly adapted to vessel motion. Since its discovery in 1976, no physical measurable parameter to quantify Sopite syndrome and its effect on performance has been established. Recent efforts to develop high-speed shallow-draft vessels, coupled with increased automation and reduced manning, have placed a premium on every crewmember. The manning modifications make it more important than ever to ensure that personnel readiness and performance degradation are accounted for in crew manning. This study quantifies Sopite syndrome and its effects on performance by using the concept of daily activity levels concurrently with ship's motion data, individual demographics and motion sickness questionnaires as input parameters to linear regression models. Presently, Littoral Combat Ship (LCS) planners are focusing on trimaran and semi-planning monohull forms as candidates for the LCS hull. Either hull form produces a different motion stimulus distribution than that of a catamaran hull. However, appropriate variable and parameter selection allows this model to be extended to any hull form.

Quantification of performance diminishment, due to motion sickness symptoms, enables reduced manning concepts

to account for unavoidable motion induced readiness reductions, and thus ensure baseline levels of performance. According to the study, participant performance levels on a three-minute manual dexterity task degraded by two to three percent over an eight-day underway period. While these numbers are not alarmingly high, the task is relatively short in duration compared to other crucial onboard tasks that can take up to six hours or an entire on-watch period. This study gives early indications that historically accepted manning assumptions should be modified to include performance degradations caused by the shipboard motion environment.

I. INTRODUCTION

A. OVERVIEW

Today’s naval battlespace is increasingly transitioning from “blue water” to “brown water” operations. To assure access in littoral regions, the U.S. Navy is developing focused capabilities in the form of the Littoral Combat Ship (LCS). The LCS is a variant of the DD(X) family of future surface combat ships; however, it is a small, specialized alternative. The LCS takes advantage of the newest generation hull form and utilizes the concepts of modularity and scalability. The focus of the LCS planning lies in mission capabilities, affordability, and life cycle costs (Littoral Combat Ship, 2008). Consequently, the new hull form requires additional investigation regarding the resulting ship motion and its effects on equipment, operations and personnel. To address these issues, the Office of Naval Research developed the Littoral Surface Craft-Experimental, referred to as LSC(X). This is a high-speed, wave-piercing, aluminum-hulled catamaran with the mission of testing a variety of technologies and human factors. The ship was christened Sea Fighter (FSF 1) on 5 February 2005 (Fast Sea Frame - FSF, 2008).

Coupled with Sea Fighter’s advances in maneuverability and hydrodynamic properties comes a departure from the ship motion experienced by the crew on traditional monohull ships. The catamaran hull form results in a more erratic distribution of ship motion with unknown effects on crew performance. Motion stimulus aboard naval vessels affects

the crew in various aspects to including: motion sickness, Sopite syndrome and motion-induced interruptions (MIIs) (Stevens & Parsons, 2002).

Motion sickness is the body's natural response to conflicting sensory input. Normally, epigastric discomfort is the first symptom followed by nausea of increasing intensity (Benson, 1999). Some individuals experience sweating, increased salivation, body warmth and light-headedness. The result of compounding these symptoms is frequently vomiting. Sopite syndrome, however, is characterized primarily by evidence of yawning, drowsiness, disinclination for physical or mental work, and lack of willingness to participate in group activities (Graybiel & Knepton, 1976). Finally, MIIs occur when ship motion causes an individual to tip or lose balance, interrupting an ongoing task. Corrective action to reduce MIIs requires a different hull form or different maneuvering of the ship, and thus is not considered in this study, which addresses manning considerations due to motion sickness symptoms and Sopite syndrome.

Throughout history, motion sickness has plagued sailors. It was observed from a survey of 699 U.S. Navy servicemen aboard destroyers that 39% never experienced motion sickness, 39% were occasionally sick, 10% were often sick and 13% were almost always sick (Bruner, 1955). While these numbers may have been manageable in the 1950s, current efforts to develop high-speed, shallow-draft vessels coupled with increased automation and reduced manning crews make it more important than ever to ensure

that personnel readiness and performance degradation are accounted for in crew manning model formulation.

B. OBJECTIVES

This study addresses performance degradation caused by Sopite syndrome by modeling psychomotor and manual dexterity task completion times using linear regression models with ship’s motion data, individual demographics, motion sickness questionnaires and daily activity levels as inputs.

At present, LCS planners are focusing on trimaran and semi-planning monohull forms as candidates for the LCS hull. Either hull form produces a different motion stimulus distribution than that of a catamaran hull. However, appropriate variable and parameter selection allows this model to be extended to any hull form.

C. PROBLEM STATEMENT

The primary research questions being investigated by this research are:

1) Can activity level or an activity-derived parameter be used as a viable input to model Sopite syndrome?
2) What is the quantitative value of performance degradation aboard the Sea Fighter caused by Sopite Syndrome on psycho-motor and manual dexterity tasks?

D. SCOPE, LIMITATIONS, AND ASSUMPTIONS

The proposed models are limited to Sopite syndrome and performance degradation in an adapted crew aboard a

catamaran hull in low sea states. Due to the indistinguishable and confounding symptoms associated with motion induced-fatigue, motion-induced sleep disruptions, boredom and Sopite syndrome, the term Sopite syndrome in this study encompasses all fatigue-related symptoms. The major assumption of both models is that the decrease in activity level as time underway increases is due solely to participant motivation, thus Sopite. This assumption is based on low participant MSAQ scores, unconstrained participant off-watch periods and observed normal sleep patterns. Model verification is not possible at this time due to the uniqueness of the transit conditions.

E. THESIS ORGANIZATION

Chapter II reviews literature discussing major causes of motion sickness and Sopite syndrome and their effect on individuals. Data collection methodology and data summary are discussed in Chapter III. It also discusses the equipment and tools utilized to gather data. Model formulation and data analysis are presented in Chapter IV. Finally, Chapter V offers conclusions and recommendations regarding the study and future research.

II. LITERATURE REVIEW

A. SEA FIGHTER HISTORY

According to the Navy Fact File (Fast Sea Frame - FSF, 2008), the Sea Fighter as seen in Figure 1, has the following general characteristics:

- Builder: Titan Corporation, San Diego
- Ship Type: Aluminum-hulled, wave-piercing catamaran
- Length: 262 ft overall, 240 ft at waterline
- Beam: 72 ft
- Displacement: 950 tons
- Draft: 11.5 ft
- Speed: 50+ knots

Figure 1. FSF-1 Sea Fighter (After http://www.defenseindustrydaily.com on 2-27-2009)

B. PHYSIOLOGICAL SYSTEMS AFFECTED BY MOTION

In order to understand how and why motion sickness occurs, it is important to know and understand the functions of the systems that are affected by a motion stimulus. Three main systems are affected by motion and result in motion sickness symptoms: vestibular, visual and proprioception.

1. Vestibular System

The vestibular system is the sensory system that provides the dominant input to the brain regarding spatial orientation, velocity and acceleration of the body. It maintains visual acuity via the vestibulo-ocular reflex (VOR) by minimizing the image motion on the retina during head/body movements. Also, the muscles that control posture and equilibrium are controlled by neural structures that receive a signal from this system (Mann, 1997). The system is composed of two component subsystems located in the labyrinth of each inner ear: the semicircular canal system and the otoliths, which can be seen in Figure 2.

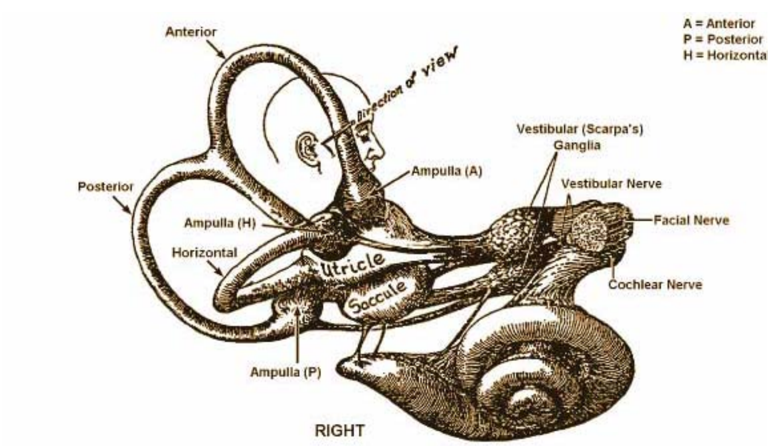


Figure 2. Inner Ear (From www.neuroanatomy.wisc.edu on 11-4-2008)

The otoliths are composed of two membranous sacs called the utricle and the saccule (Howard, 1986). The utricle is located horizontally and is sensitive to changes in the horizontal plane, while the saccule senses gravity and accelerations in the vertical plane (Mann, 1997). The motion is sensed when the otolith hairs, seen in Figure 3, are subjected to movement in the otolithic membrane caused by head motion.

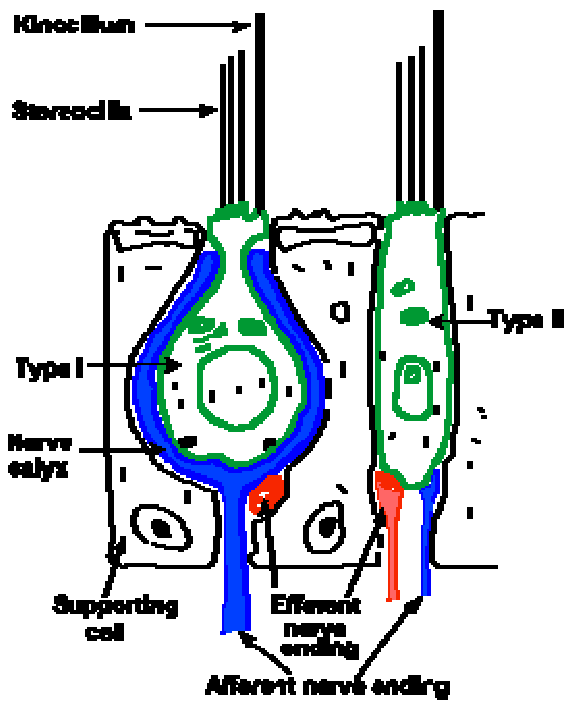


Figure 3. Cross section of Otolith (From www.unmc.edu/physiology on 11-4-2008)

The semicircular canal system contains three endolymph-filled semicircular ducts that are nearly orthogonal to one another (Mann, 1997). The horizontal, superior and posterior semicircular canals sense rotational acceleration in the x, y and z axes. A cross-section of a canal is illustrated in Figure 4. Each canal has a corresponding partner in the labyrinth on the opposite

side. Motion is sensed when a change in head rotation speed causes the endolymph fluid to sluggishly lag behind the motion of the duct due to inertia. The nervous system receives the vestibular sensory information from the otoliths and the semicircular canal system and correlates the data to generate an integral response to head motion (Angelaki, Merfield & Hess, 2000).

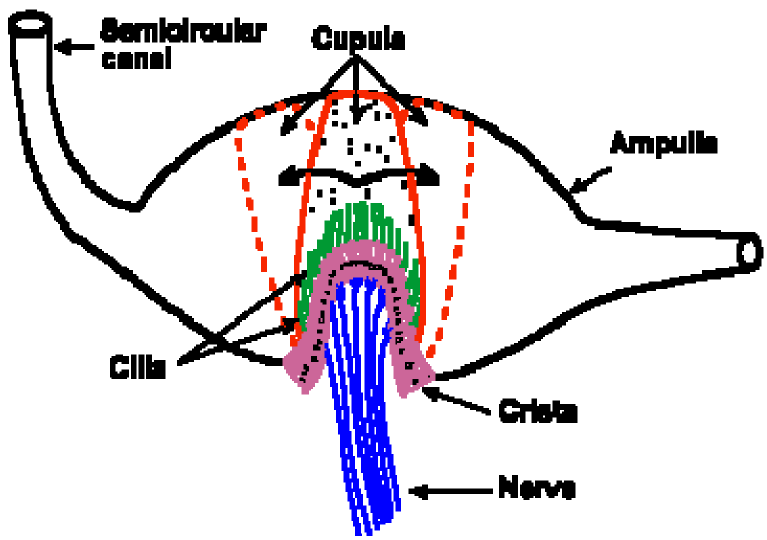


Figure 4. Cross section of Semicircular Canal (From www.unmc.edu/physiology on 11-4-2008)

2. Visual System

The visual system is a subsystem of the nervous system. Composed mainly of the eyes, the visual system translates electromagnetic waves of light into a two dimensional image on the retina. The two-dimensional projection is then transmitted to the brain via nerve impulses where it is transformed into a three-dimensional object that is perceived by the individual (Eye, 2008). Figure 5 shows a cross-section of the human eye.

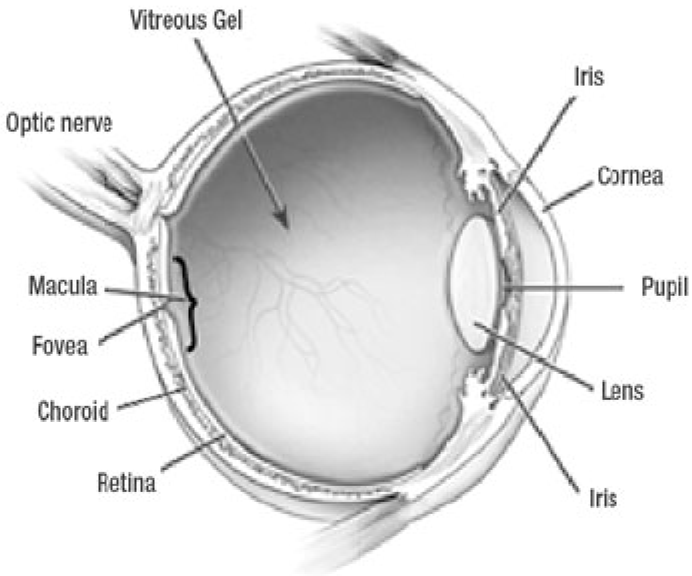


Figure 5. Cross section of Eye (From www.gene.com on 1-20-2009)

3. Proprioception

The proprioceptive channel is a rich set of systems located within all of the muscles and joints of the body. The system conveys to the brain an accurate representation of muscle contraction and joint angles, and therefore limb position in space (Wickens, Sallie & Liu, 2004). Contraction, compression and stretching are sensed by receptors in the joints, tendons and muscles. This system allows an individual to perform tasks such as pushing, pulling and carrying objects without having to look at each body part while in motion.

C. MOTION SICKNESS

1. Motion Sickness Description

Motion sickness as defined by Webster’s Dictionary is “the state of being dizzy or nauseated because of the motions that occur while traveling in or on a moving

vehicle" (Motion Sickness, 2008). The term itself implies a sickness directly caused by motion felt by an individual. While this is partially true, motion is not necessary to cause motion sickness and the anomaly is not actually a sickness at all, it is the body's natural response to conflicting sensory input. Normally, epigastric discomfort is the first symptom followed by nausea of increasing intensity (Benson, 1999). Some individuals experience sweating, increased salivation, body warmth and light-headedness. The result of compounding these symptoms frequently results in vomiting. Figure 6 illustrates the general timeline of motion sickness induction (MSI) over time. The graph is interpreted as the percentage of unadapted individuals who vomit when exposed to a given motion. The crest is reached approximately two hours after motion begins, then decreases to zero within 60 hours.

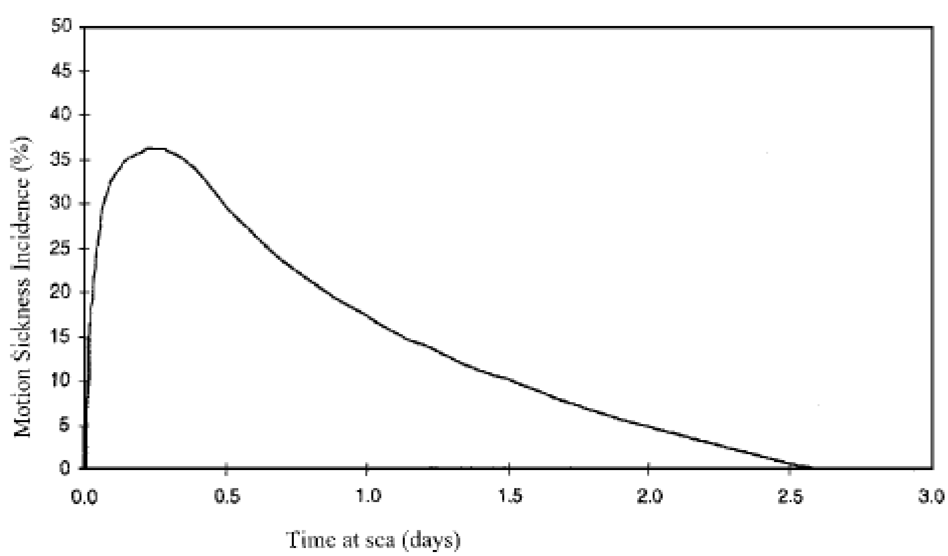


Figure 6. Motion sickness incidence (MSI) over time (From Crossland, 1998)

2. Causes of Motion Sickness

Motion sickness is fundamentally a vestibular process. There are several accepted theories surrounding the causes of motion sickness. However, most rely on the condition of contradictory sensory input. Some of the most widely accepted theories are the neural mismatch theory (Benson 1999), conflict mismatch theory and sensory rearrangement theory (Reason & Brand, 1975). These theories are all variations of the same theme. Wertheim (1998) states that the theories above attribute the cause of motion sickness via the same proposition: The vestibular information supplied to the brain regarding self motion does not agree with the visual system, kinesthetic system or what is expected from previous experience. The conflicts occur in either an inter-sensory or intra-sensory manner. Inter-sensory conflict occurs when incompatible signals are sensed from two of the primary sensory systems. Intra-sensory conflict occurs when signals within a single system are incompatible. Tables 1 and 2 depict the types of conflicts and the motion cue mismatch by various stimuli.

Table 1. Types and Categories of sensory conflict (From Griffin, 1991)

Type of Conflict	Category of Conflict	
	Intersensory (Visual – Vestibular)	Intrasensory (Canal – Otolith)
Type I	Visual and vestibular systems simultaneously signal different (i.e. contradictory or uncorrelated) information	Canals and otoliths simultaneously signal different (i.e. contradictory or uncorrelated) information
Type II	Visual system signals in the absence of an expected vestibular signal	Canals signal in the absence of an expected otolith signal
Type III	Vestibular system signals in the absence of an expected visual signal	Otoliths signal in the absence of an expected canal signal

Table 2. Types of motion cue mismatch produced by various stimuli (From Griffin, 1991)

Type of Conflict	Category of Motion Cue Mismatch	
	Intersensory (Visual [A] – Vestibular [B])	Intrasensory (Canal [A] – Otolith [B])
Type I A and B simultaneously signal different (i.e. contradictory or uncorrelated) information	Watching waves from a ship Use of binoculars in a moving vehicle Making head movements when vision is distorted by optical device "Pseudo Coriolis" stimulation	Making head movements whilst rotating (Coriolis or cross-coupled stimulation) Making head movements in an abnormal acceleration environment which may be constant (hyper – or hypo-gravity) or fluctuating (linear oscillation) Space sickness Vestibular disorderd
Type II A signals in the absence of an expected B signal	Cinerama sickness Simulator sickness Circular vection	Positional alcohol nystagmus Caloric stimulation of semi-circular canals Vestibular disorders
Type III B signals in the absence of an expected A signals	Looking inside moving vehicle without external reference; below deck in a boat Reading in a moving vehicle	Low-frequency (<0.5 Hz) translational oscillation Rotating linear acceleration vector ("barbeque spit" rotation, rotation about an off-vertical axis)

3. Motion Sickness Susceptibility & Adaptation

According to Griffin, there is wide variation in the susceptibility of an individual to motion sickness (Griffin 1990). The variation is a function of psychological variables such as personality, past motion exposure and adaptability. Furthermore, an individual's dependency on

vestibular, visual or proprioceptive information can cause intra-subject and inter-subject variability in the propensity to develop motion sickness (Griffin, 1990). There are also observed predisposing factors that can affect an individual’s susceptibility such as sex (Benson, 1999), age (Benson, 1999), sleep history (Dowd, 1974) and personality (Guedry, 1991). Adaptation does not take place in approximately five percent of the population (Hemingway, 1945; Tyler & Bard, 1949). According to Reason & Brand (1975), the body expects its sensory systems to send signals in recognizable combinations at every instant in time. When the contrary occurs, the body is subject to motion sickness. However, over time the brain learns new combinations resulting from the sensory environment, thus enabling adaptation. The susceptibility of an individual is a function of the rate at which the brain recognizes updated combinations. According to Reason (1972), there are three characteristics that affect the rate of recognition: receptivity, adaptability and retentiveness. Receptivity refers to the motion stimulus signal amplification within the individual. Adaptability refers to the rate at which the internal model updates to the revised signal combinations. Retentiveness refers to an individual’s ability to retain the internal model of signal combinations and adjust to motion in succeeding motion exposures (Reason, 1972). Figure 7 shows the predicted adaptation effects of sensory rearrangement according to the Neural Mismatch Model.

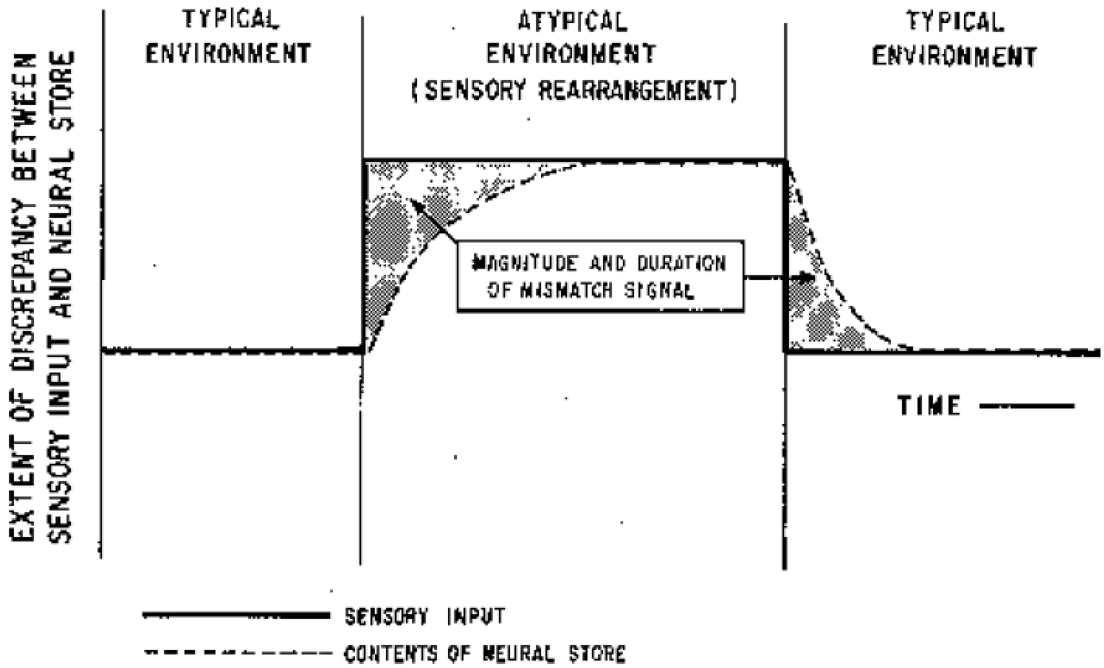


Figure 7. Neural Mismatch Model predicted adaptation effects of sensory rearrangement (From Reason & Graybiel, 1973)

There are numerous pharmacological methods of controlling motion sickness and its effects on behavior. Scopolamine, promethazine hydrochloride and antihistamines are medications that may prevent motion sickness (Motion Sickness: Treatment Overview, 2007). There also exists the Puma Method that submits it can prevent motion sickness completely naturally. The Puma Method was developed by Dr. Sam Puma to combat the effects of motion sickness in various environments. The method consists of a series of simple head movement exercises that purportedly raises one’s tolerance to motion sickness (About the Puma Method, 2008). The method is intended to train the participant’s brain to process conflicting sensory inputs, thus resulting in adaptation prior to exposure to a motion stimulus.

4. Motion Sickness Methods of Measurement

There has been much work in the field of predictive models. There are two widely accepted models for predicting Motion Sickness Incidence (MSI).

- Motion Sickness Incidence (MSI), McCauley and O'Hanlon (1974)

- Vomiting Incidence (VI), Lawther and Griffin (1987 & 1988)

Both models express MSI as a percentage of personnel exposed to motion. A comparison of the two models was conducted on data obtained from 73 ship motion conditions: 51 ship motion simulator experiments and 22 at-sea conditions. The comparison shows that the MSI model has a 3% average error with a standard deviation of 7%, while The VI model has an average error of 4% and a standard deviation of 9% (Colwell, 1994).

Currently, the International Standard Organization (ISO 2631, 1997) and British Standard Organization employ the VI model for predicting MSI. The standard uses a Motion Sickness Dose Value ($MSDV_z$) to determine the total dose applied by a given motion stimulus. MSI is used to determine the percentage of persons likely to vomit following exposure to vertical oscillations less than 0.5 Hz.

$$MSDV_z = \left[\int_0^T [a_w(t)]^2 \, dt \right]^{1/2}$$

$$MSI = MSDVz * \frac{1}{3}$$

where:

- $a_w(t)$ is the frequency-weighted acceleration in the z direction;
- T is the total period (in seconds) during which motion occurs;
- Km is a constant that varies according to population. Km ≈ 1/3 for a mixed male and female population.

The Motion Sickness Assessment Questionnaire (MSAQ) is a survey tool used to determine the degree to which an individual is suffering from motion sickness symptoms. Motion sickness is an aversive behavioral condition that affects numerous psycho-physiological sensory systems. Generally, multiple systems are triggered by the sensation of motion; therefore the individual is most likely referring to a complex array of symptoms when referring to “motion sickness” (Gianaros et al., 2001). In an effort to differentiate the symptoms from the various sensory systems, Gianaros et al. (2001) developed the MSAQ to assess the following four dimensions of motion sickness: gastrointestinal, peripheral, central and Sopite. Since individuals experience differing degrees of motion sickness, the MSAQ allows researchers the ability to quantify symptom dimensions (Gianaros et al., 2001). The questionnaire, Figure 8, is composed of 16 questions with a response range of one to nine. Each question requires the participant to rate their condition regarding a motion sickness symptom. A score of one means the participant did

not experience the symptom while a score of nine means that the participant severely feels the symptom.

APPENDIX A. MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ).

Instructions. Using the scale below, please rate how accurately the following statements describe your experience.

Not at all — Severely
1——2——3——4——5——6——7——8——9

1. I felt sick to my stomach (G)
2. I felt faint-like (C)
3. I felt annoyed/irritated (S)
4. I felt sweaty (P)
5. I felt queasy (G)
6. I felt lightheaded (C)
7. I felt drowsy (S)
8. I felt clammy/cold sweat (P)
9. I felt disoriented (C)
10. I felt tired/fatigued (S)
11. I felt nauseated (G)
12. I felt hot/warm (P)
13. I felt dizzy (C)
14. I felt like I was spinning (C)
15. I felt as if I may vomit (G)
16. I felt uneasy (S)

Note. G: Gastrointestinal; C: Central; P: Peripheral; SR: Sopite-related. The overall motion sickness score is obtained by calculating the percentage of total points scored: (sum of points from all items/144) × 100. Subscale scores are obtained by calculating the percent of points scored within each factor: (sum of gastrointestinal items/36) × 100; (sum of central items/45) × 100; (sum of peripheral items/27) × 100; (sum of sopite-related items/36) × 100.

Figure 8. Motion Sickness Assessment Questionnaire (From Gianaros et al., 2001)

D. SOPITE SYNDROME

1. Sopite Syndrome Description

Unlike the recognizable physiological symptoms normally associated with motion sickness, there exists a subtle subcategory of fatigue related symptoms. According to Graybiel & Knepton (1976), these more subtle effects are merely part of a symptom-complex termed Sopite syndrome. Symptoms of Sopite syndrome regularly remain unnoticed and are not drastically felt such as yawning, drowsiness, headaches and feelings of indifference to one’s fate (Griffin, 1990). Graybiel and Knepton (1976) characterized Sopite syndrome primarily by evidence of yawning,

drowsiness, disinclination for physical or mental work, and lack of willingness to participate in group activities. Graybiel and Knepton (1976) also noticed a variety of other related symptoms: lethargy, apathy, decreased ability to concentrate, daydreaming, melancholy, sleep disturbances, performance errors, frequent daytime napping, irritability, and a desire to be left alone. These symptoms generally occur rapidly following initial exposure and persist well after nausea subsides (Dobie, 2003). In many cases, Sopite syndrome may be a sole manifestation of motion sickness (Lawson & Mead, 1998). Sopite syndrome affects human performance in a variety of Ways. According to Wertheim (1998), fine motor skills and visual detail of small objects can be affected by motion. However, due to the nature of the symptoms, performance decrement is rarely identifiable by the individual or the supervisor. While the effects of sopite can be overcome by adrenaline in a hazardous or emergency situation, a lapse in attention or crew performance can jeopardize a mission (Lawson & Mead, 1998).

2. Causes of Sopite Syndrome

Although Sopite syndrome has been identified since 1976, it is a poorly understood phenomenon resulting from the body’s response to a motion stimulus.

3. Sopite Syndrome Method of Measurement

Although researchers are aware of Sopite syndrome, there has been little progress regarding quantifying it other than the Sopite sub-scale of the MSAQ. Due to confounding variables involved with the study of human

subjects, and without specific knowledge of the causes of Sopite syndrome, no objective measurable physical parameter has been established. Subjective measurements are available via the MSAQ Sopite subscale, but require participant reporting. Furthermore, the reliability and validity of a four-question test is low. There have, however, been studies that attempt to model depressed moods by measuring psychomotor retardation. Wells et al. (1989) reported lower physical, social, and role functioning, poorer perceived current health, and more bodily pain in depressed individuals with depressive symptoms than healthy individuals. Mendlowicz et al. (1999) investigation suggests that in a non-psychiatric sample daytime activity level, as assessed by wrist actigraphy, can be used as an index of depressed mood (Mendlowicz et al., 1999). Depressed moods as defined in the study are expressions of sadness, discouragement or feeling down, which closely resemble the symptoms of Sopite syndrome.

III. METHODOLOGY

A. PARTICIPANTS

The data set was collected aboard the FSF-1 Sea Fighter from May 16, 2008, to June 2, 2008. The collection process took place as the ship transited from Panama City, FL, to San Francisco, CA. The data set is composed of 16 participants all of whom were male. Among the 16 participants, 12 were civilian contractors normally attached to the ship and four active-duty Navy servicemen riding the ship. Among the crewmembers, there were five individuals who chose not to participate in the study. All not participating were located in the Engineering Department. Eight participants volunteered to be part of the Puma Method; however, only five participants actually performed the exercises.

B. EQUIPMENT

1. SPDAS

The Scientific Payload Data Acquisition System (SPDAS) and Panama City Division’s Motion Data Acquisition System (MDAS) was used to collect ship motion data. Temporarily installed accelerometers were used to collect roll, pitch, yaw, x, y and z axis data values (Pierce, 2008). The Computer Aided Central Timing Unit system (CACTUs), seen in Figure 9, receives input from the accelerometers and stores the dynamic data with a GPS time stamp, vessel heading, speed and location (Pierce, 2008). The data is sampled and stored at a frequency of 750 Hz

Figure 9. Computer Aided Central Timing Unit system (CACTUs)(From Pierce, 2008)

2. TSK Wave Height Meter

The ship is equipped with a TSK Wave Height Meter System. The system is mounted on the frame centerline on the bow of the ship. The system uses a microwave sensor unit to monitor wave height and period (Pierce, 2008). The TSK displays wave height as a 20 min moving average. To facilitate an accurate reading, the ship slowed for 20 minutes to five knots while TSK operations in progress.

3. Actigraphs

Actiwatch®-64, shown in Figure 10, is a small rugged wrist-mounted accelerometer used to measure and record gross motor activity. The internal accelerometer sensitivity is 0.05 g-force and has an acceleration bandwidth of three to eleven Hz. The actigraph samples at a frequency of 32 Hz and was initialized for a one-minute epoch length (Actiware® 5.0, 2004). The actigraph data output is in the form of counts per minute, shown in Figure 11, and is normally used to determine various sleep characteristics and quality. In this study, it is also used to measure activity levels of participants while

awake. Figure 11 shows the data manipulation graphical user interface in the Actiware® software. Each black column represents the number of times that the accelerometer sensed an acceleration greater than 0.05 g-force for a given minute.

Figure 10. Actigraph (From www.umdnj.edu on 1-21-2009)

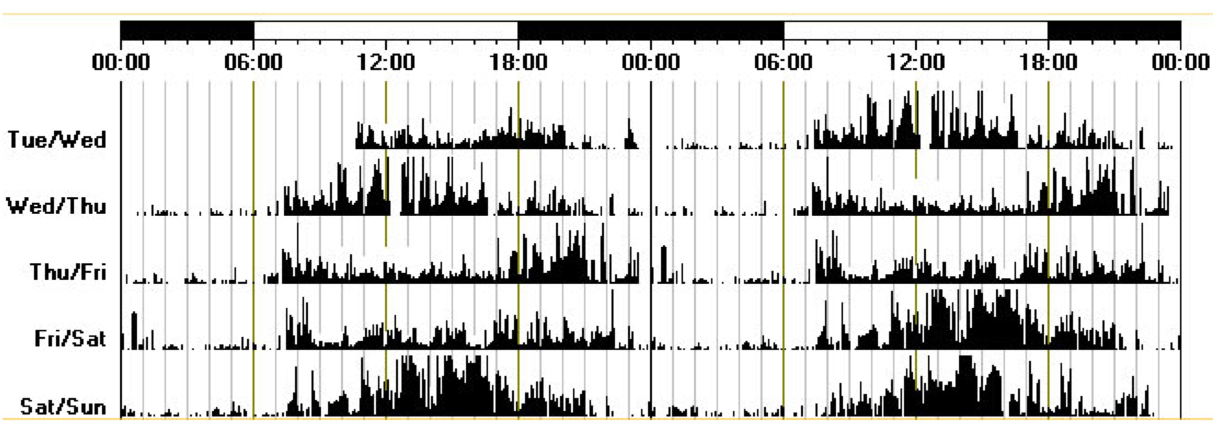


Figure 11. Sample Actigraph output (From www.istitutodineuroscienze.it)

C. PERFORMANCE TESTS

1. Functional Range of Motion (FROM)

The FROM, developed by BTE Technologies, is a standardized industrial skill assessment device used to compare abilities of a worker to accepted Methods Time Measurement (MTM) standards. MTM is a procedure used to "assign pre-determined time standards to a task by recognizing, classifying and describing the motions used to perform given operations (MTM, 2008)." The FROM, which is a vertical pegboard test of manual dexterity, emulates some of the manual handling tasks anticipated on the LCS. It can be used to assess the impact vessel dynamics has on human performance based on time and error rate. Each FROM task trial is composed of two segments. During the first segment, participants were asked to remove each peg from the left panel with their left hand and place it in the corresponding position in the right panel using their right hand. Once all pegs were removed from the left panel, the same procedure was used in reverse to return the pegs to their original location. This sequence was repeated three times to complete the first segment of the test. During the second segment, participants were asked to complete the same task from the stooping position. Time to complete and number of errors were recorded for both the standing and stooping portions of the test. Figure 12 illustrates the standing and stooping positions.

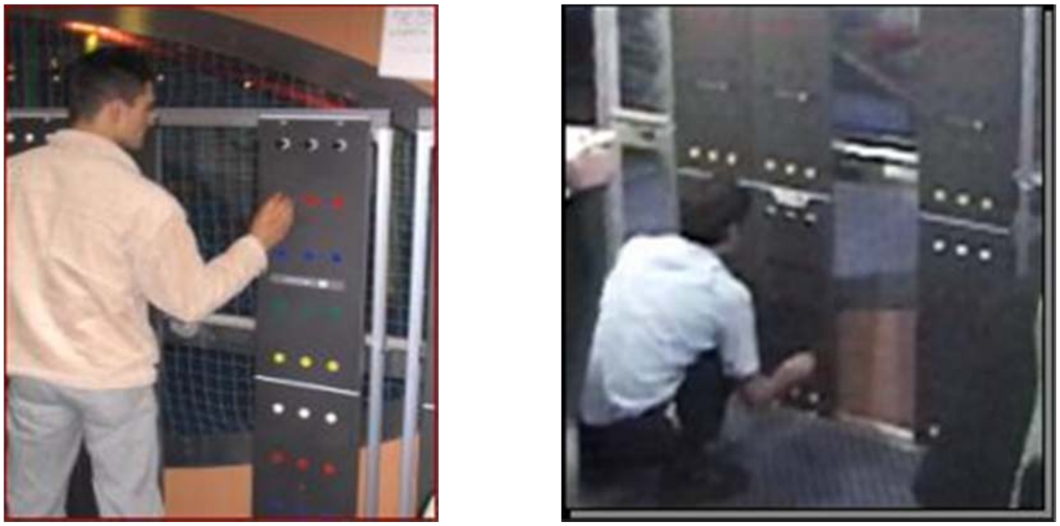


Figure 12. Functional Range of Motion (From McCauley, Pierce & Matsangas, 2007)

2. Mirror Tracer

The Mirror Tracer, shown in Figure 13, is an instrument used to analyze the psycho-motor capabilities of a participant. The mirror tracer requires a subject to reverse visual cues and trace a mirrored star pattern with an electrical stylus. Due to the metal screen, participants are unable to view their hands directly while tracing. Rather, the participants viewed their hands via the mirror. Each test consists of the participant tracing the star once. The apparatus counts the number of errors that occurred for each trial while the task proctor times the test for duration. This procedure was completed for each hand.

Figure 13. Mirror tracer (From www.rehaboutlet.com on 1-21-2009)

D. PROCEDURE

Two weeks prior to departure from Panama City, eight volunteers were selected to perform the Puma Method. Each volunteer was given a Puma Method instructional video and a head mounted accelerometer that measures intensity of head movement by time and caloric expenditure. Prior to transit departure, while the ship was moored in Panama City, Fl, all participants completed pre-underway questionnaires and were issued actigraphs. Participants were asked to wear the actigraphs at all times throughout the transit and to complete sleep logs for all periods of sleep. Participants were asked to complete MSAQs every four hours for the first 24 hours following any departure underway, and every twelve hours on non-underway days. If participants failed to complete daily MSAQs as requested, the Test Coordinator

verbally obtained MSAQ input and entered it into the MSAQ database. To determine the relationship between MSI, Sopite syndrome and performance degradation, the mirror tracer and FROM tasks were performed at variable wave heights throughout the transit. The tasks were performed prior to getting underway in Panama City, FL to establish a baseline and following departure from Panama City, Panama, and Long Beach, CA. Tasks were also performed following any significant, more than three feet, change in wave height. Prior to testing, each testing day, the ship slowed for 20 minutes to facilitate a TSK wave measurement. Participants were tested throughout the day as they became available and were willing to do so.

Each crewmember stood watch at the same time each day and was on watch twice daily with eight hours off between watches, thus negating the effects of a rotating watch schedule on fatigue levels. During the transit, crewmembers were allowed to spend their off-watch time as they pleased. For the entire transit, one hour of maintenance for two personnel, one hour of optional training and no drills occurred. Thus, daily activities were left entirely up to the motivation and judgment of the individual. To ensure that all participants were operating with a consistent level of motivation from one trial to the next, the participant with the overall best time on the FROM task was excluded from standing duty while in Panama City, Panama.

Throughout the transit, the ship saw varying levels of wave height, but only experienced levels greater than six feet on the last day. Additionally, due to time

constraints, the ship’s speed was relatively constant throughout the transit. Furthermore, the relative direction of the seas was within 45 degrees of ship’s head throughout the entire transit.

IV. MODEL FORMULATION & RESULTS

A. DATA COLLECTION RESULTS

Descriptions of all parameters collected or measured are located in appendices A, B and C. The data set presents a unique opportunity to filter unwanted noise from the data by maintaining several variables essentially constant. While the sea conditions were poor for investigating MSI, they were excellent for the investigation of Sopite. The crew failed to appropriately complete sleep logs, thus preventing analysis of sleep quality and duration. However, due to a constant watch rotation and unconstrained off-watch periods the crew was not forcibly sleep-deprived. An examination of the sleep data shows that participants obtained sleep patterns that were normal in both quality and duration. Since the crew was adapted to the relatively constant motion stimulus and motion-induced interruptions were not significant while testing, performance degradation should solely have been due to participant level of effort. Due to the long adaptation period prior to significant seas, participants that volunteered to perform the Puma Method showed no less susceptibility to motion sickness symptoms. It should be noted that two civilian contractors boarded the ship prior to departure from Long Beach, CA and suffered greatly from motion sickness during the higher sea-state the following day. The fact that the contractors became motion sick and the crew did not supports the notion that adaptation had taken place in the crew, thus any performance degradation in the higher sea-state could also be attributed to Sopite.

Descriptive crew, ship and environmental statistics can be located in Tables 3 and 4 below.

Table 3. Descriptive Statistics: Crew

Variable	Number of Subjects	Total Number of Trials	Min	Max	Mean	Std Dev
PUMA logs (Time: Minutes)	5	23	7	30	16.83	6.79
PUMA logs (Calories)	5	23	7.8	19.2	13.44	4.38
Mirror Tracer Time (Dominant Hand)	15	100	13	130	40.12	23.23
Mirror Tracer Error (Dominant Hand)	15	100	0	19	4.03	4.19
Mirror Tracer Time (Non-Dom Hand)	15	100	13	132	37.06	19.95
Mirror Tracer Error (Non-Dom Hand)	15	100	0	32	5.66	5.60
FROM Standing (Time: Sec)	15	99	162	259	210.08	21.02
FROM Stooping (Time: Sec)	15	93	157	300	203.59	29.29
Actigraph Participants	14	Daily	N/A	N/A	N/A	N/A
MSAQ (Total Score)	16	442	11.11	54.17	12.43	4.70
MSAQ (Gastro)	16	442	13.89	100.00	15.22	8.85
MSAQ (Peripheral)	16	442	11.11	96.30	13.74	9.92
MSAQ (Central)	16	442	11.11	40.00	11.47	2.92
MSAQ (Sopite)	16	442	11.11	44.44	12.94	5.64
Age	16	N/A	19	50	34	10.3
Weight	16	N/A	160	350	211.6	45.8
Handedness	16	Right Handed: 14 Left Handed: 2				
Introverted/ Extroverted	16	Introverted:12 Extroverted: 4				

Table 4. Descriptive Statistics: Ship and Environmental

Parameter	Total Number of Trials	Min	Max	Mode	Std Dev
Logged Wave Height (Feet)	Hourly (293)	1	8	2	1.50
Wave Period (Seconds)	Hourly (293)	2	5	4	0.68
Relative Direction of Seas	Hourly (293)	0	7	0	3.06
Ship's Heading (Degrees)	Hourly (293)	132	355	296	67.36
Ship’s Speed (Knots)	Hourly (293)	0.00	22.30	16	2.72

B. DERIVED DATA

The Proportional Activity Degradation (PAD) was calculated per Appendix G. First, each actigraph was programmed to initiate at 1800 Central time on May 16, 2008. Actigraphs were distributed to participants on May 15, 2008, and May 16, 2008. The actigraphs were collected from participants on June 2, 2008. Actigraph data for each participant was downloaded to the Minimitter software. Next, the data was analyzed to determine periods of sleep and activity. This step was particularly difficult due to the lack of participant sleep logs. Only periods of unquestionable activity were categorized as active. All periods of unknown status were excluded. Following the status determination of all active, sleep and excluded periods, the data was exported to a spreadsheet. The export file contained the activity level and status for each minute of the transit. The dates and times were then corrected to account for a two-hour time change from

Central to Pacific Time. The activity level for each active minute was summed for each day and divided by the number of active minutes that day. The calculation was completed for each participant for each day of the transit. This calculation resulted in an average activity level during known activity periods for each participant for each day. The daily participant PAD was calculated by subtracting the activity for the specific day from the activity on the day of the last departure from port, the baseline. The difference was then divided by the baseline activity resulting in the proportional decrease in activity since the last underway. The PAD for person i on day j of leg g is given by the following equation:

$$PAD_{ijg} = \frac{ACTIVITY_{i1g} - ACTIVITY_{ijg}}{ACTIVITY_{i1g}} \quad \forall \text{ i,j,g}$$

where

- $ACTIVITY_{ijg}$ is the activity level for person i on day j on leg g.
- $ACTIVITY_{i1g}$ is the activity level for person i on day 1 of leg g.

If the participant did not have an activity score for the day of the last departure, then the day after departure was used as the baseline.

C. LIMITATIONS OF DATA

Due to the circumstances involved with working with volunteers, not all study members participated every day of the testing. During the transit, some individuals refused to participate on various days for multiple study parameters. Motivation to complete the study was low for

several crewmembers due to uncertainty surrounding job security upon arrival at Portland. Improper sleep log completion resulted in the inability to use actigraph data for quantitative sleep analysis. There exists small variance in MSAQ scores throughout the transit due to no appreciable seas being encountered prior to the adaptation period. Furthermore, crewmembers may have failed to divulge true motion sickness symptoms due to professional pride as a seaman. At least two instances involved a participant who vomited and did not report on next MSAQ. The error rate from the FROM test was not usable due to the difficulty in error determination during testing. There is large variability in participants’ age, 19 - 50 years, and weight, 175 – 350 lbs. Furthermore, participant sea time experience ranged from 0 – 26 years. Also, participants stood watch in different parts of ship, thus exposing watchstanders to different environments of smell, temperature and motion.

D. MODEL INPUT DATA POINTS

Mirror tracer performance tasks are categorized into 143 data points by dominant and non-dominant hand. Functional range of motion performance scores are categorized into 147 data points by standing and stooping posture. Associated with each data point are the parameters listed in appendices A, B and C. Data from Appendix C was obtained via the pre-deployment questionnaire. MSAQ, MEDS and MEQ2 scores assigned to each data point correspond to the most recent MSAQ. ACTIVITY scores assigned to each data point correspond to the individual ACTIVITY score for the day of performance task

testing. PAD score assigned to each data point corresponds to the proportional activity degradation using the day of the last underway as a baseline. WAVE HEIGHT, HEADING, Aw and SEAS for each data point correspond to the logged values for the hour the individual's test took place. TSK wave height corresponds to the TSK measurement for that day. Errors on the FROM task were excluded for each data point due to the difficulty of measurement.

E. SOPITE MODEL FORMULATION

Before Sopite can be modeled by regression coefficients, relationships between activity level and other variables must be investigated. The strongest relationship found was between the number of days underway since the last period in port and daily activity level.

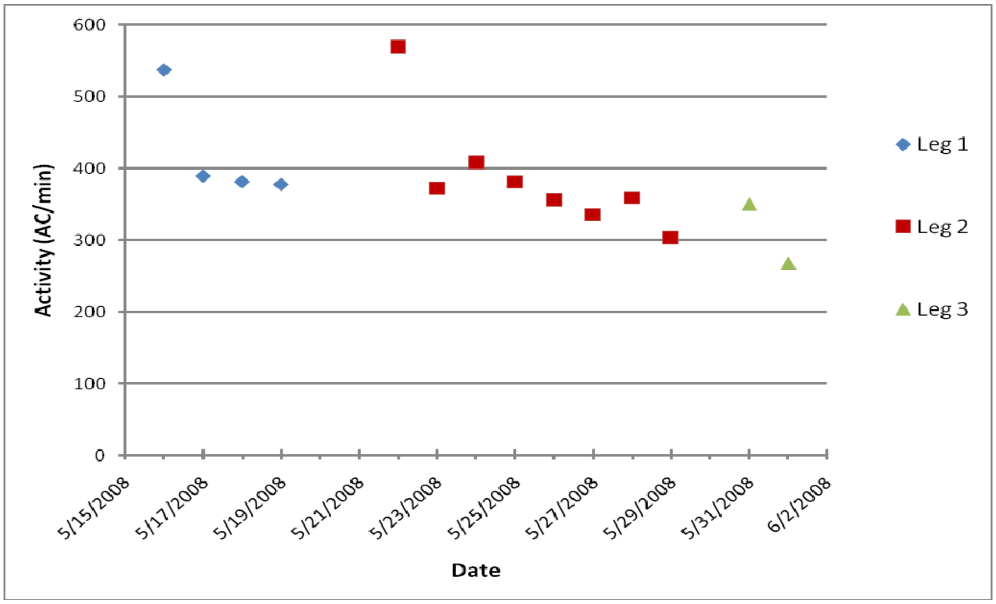


Figure 14. Average Group Daily Activity vs. Zulu Date

Figure 14 shows the average crew activity levels for each day of the transit. It can be seen by the shape of the data plot that activity levels decay as time underway increases and follow the general form:

$$Activity_{Day} = Activity_{o} * Day^{(DC)}$$

where

- $Activity_{Day}$ is the activity on any given day;
- DAY is the number of consecutive days since the last day the ship got underway;
- DC is a decay constant.

To obtain the approximating decay function for each leg, a non-linear regression by least absolute deviations (LAD) was performed. Using the Excel Premium Solver, a decay constant was selected such that the sum of the absolute value of the differences between the computed decay function and the actual averaged daily values for each leg of the transit was minimized. The non-linear programs can be found in Appendix E. The resulting decay constants for leg one and two are 0.318 and 0.296. The decay constant for leg three has a much steeper negative slope with a decay constant of 0.386; this may be attributed to the heavy seas incurred on day two of the third leg.

The resulting approximating decay functions for legs one, two and three are:

$$Activity_{Day} = Activity_o * Day^{(-.318)} \quad \text{(leg 1)}$$

$$Activity_{Day} = Activity_o * Day^{(-.296)} \quad \text{(leg 2)}$$

$$Activity_{Day} = Activity_o * Day^{(-.386)} \quad \text{(leg 3)}$$

Figure 15 depicts the decay functions graphically.

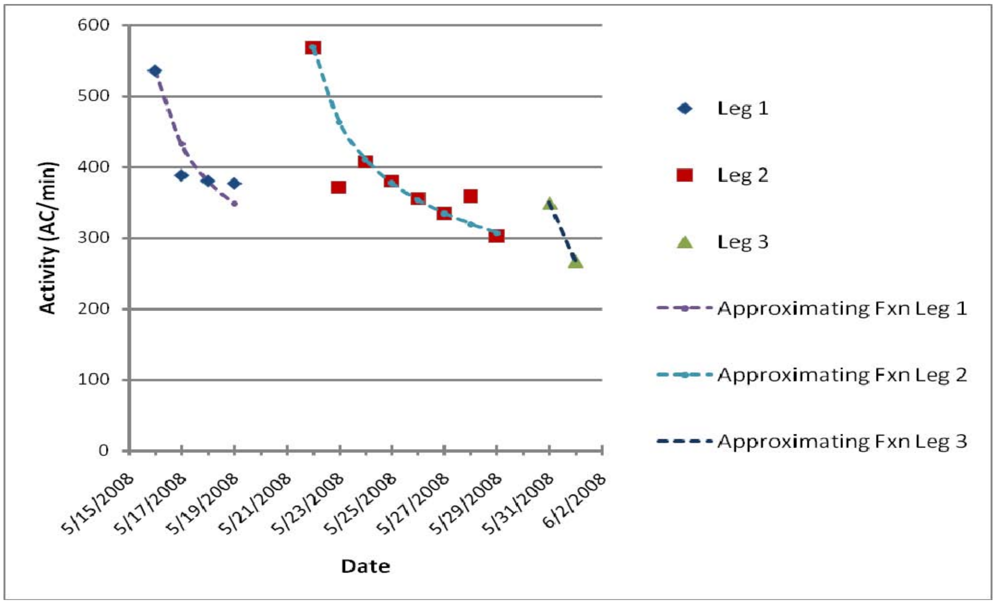


Figure 15. Average Group Daily Activity Decay Function vs. Zulu Date

Interestingly, the initial activity levels of legs one and two are of similar magnitude, but the initial activity level of leg three is much smaller. The reduced initial value may be due to the extremely short period in port prior to leg three – approximately 33 hours compared to the 68 hours in port prior to leg two and months in port prior to leg one, resulting in a “savings” of symptoms from the previous leg. Considering legs one and two to be

independent data sets with comparable motion environments, the data can be combined to generate a function that models activity level by days underway. Due to the short in port period prior to leg three and heavy seas during that leg, it is excluded. To merge the data, leg one and two participant daily activity levels were averaged to obtain an average level for each day underway. This operation combines leg one and leg two such that the new transit average activity level reflects the average activity level for both legs for a specific amount of time underway. Figure 16 shows the data transformation graphically.

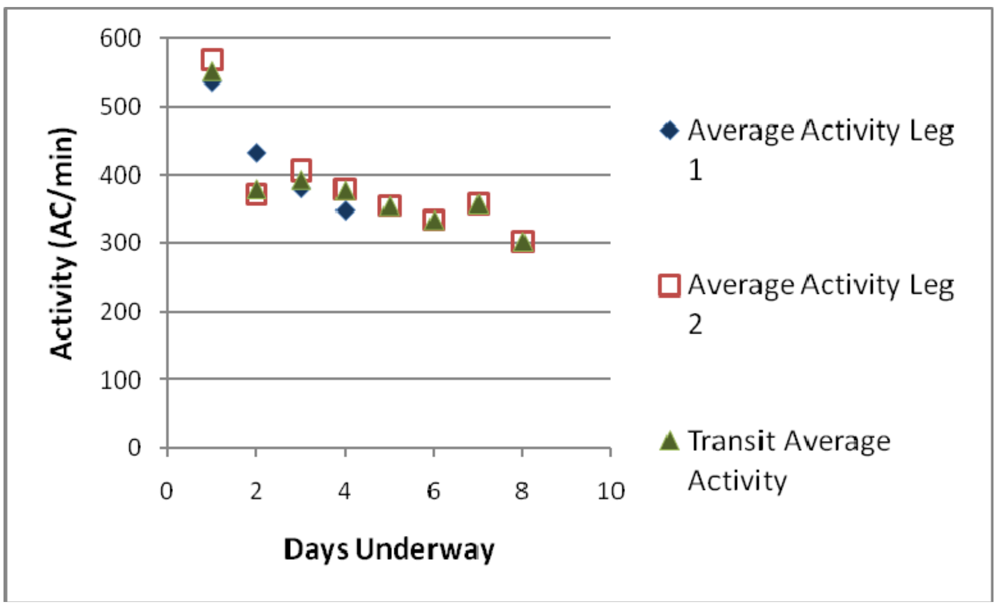


Figure 16. Average Group Daily Activity vs. Days Underway

Next, the transit activity level approximating decay function was obtained by performing one more non-linear regression by LAD. Using Excel Premium Solver, a decay constant was selected such that the sum of the absolute value of the differences between the computed decay function and the actual averaged daily values for the

transit was minimized. The non-linear program can be found in Appendix F. The transit activity function decay constant is .280, resulting in the following transit Activity level function:

$$Activity_{Day} = Activity_{o} * Day^{(-.280)}$$

Figure 17 depicts the decay function graphically.

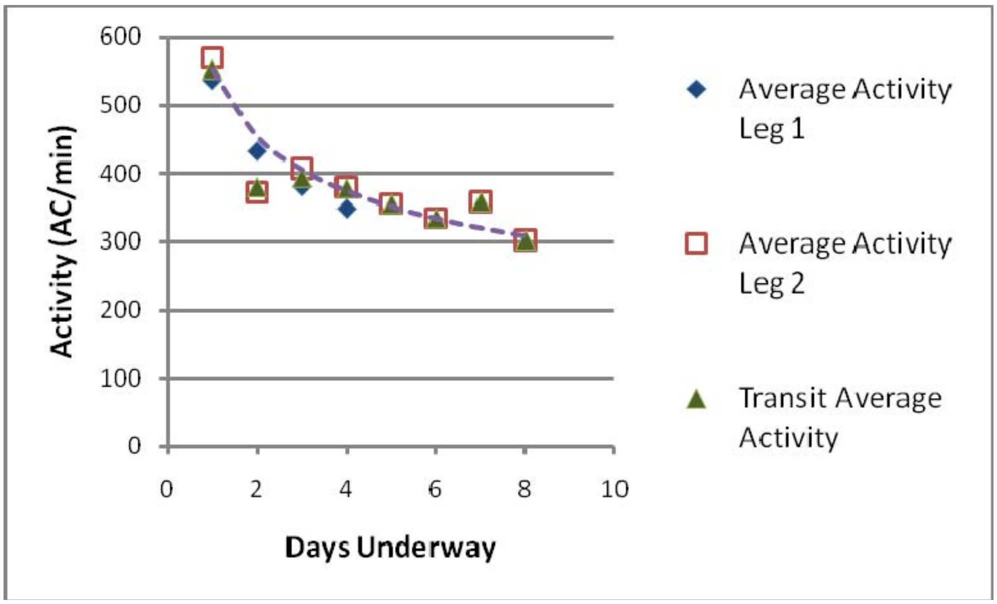


Figure 17. Transit Activity Decay Function vs. Days Underway

Since activity levels vary from participant to participant, using the value of activity does not indicate how a participant is affected by Sopite. Sopite syndrome is not associated with overall baseline activity level when not subjected to a motion stimulus, but the proportional change in activity level once the symptoms occur. Thus by calculating the proportional change in activity level for each participant from day to day, a normalized value is obtained. This value allows the comparison of all participants while removing magnitude-based bias. Using

the combined transit data, the proportion of activity degradation (PAD) was calculated for each day underway using the equation:

$$PAD_{ijg} = \frac{ACTIVITY_{i1g} - ACTIVITY_{ijg}}{ACTIVITY_{i1g}} \;\; \forall \text{ i,j,g}$$

where:

- $ACTIVITY_{i1g}$ is the activity of person i on the first day of leg g;
- $ACTIVITY_{ijg}$ is the activity of person i on day j of leg g.

Following the proportional activity degradation, the average proportion of activity degradation (APAD) was calculated for the entire crew for each day by the following equation:

$$APAD_j = \frac{\sum_{i,g} PAD_{ijg}}{2} \;\; \forall \text{ j}$$

where

- PAD_{ijg} is the proportional activity degradation for person i on day j on leg g.

The full method of calculation can be seen in Appendix G. The result of this calculation is a value for each day, of any leg, that represents the average proportional activity degradation of a crewmember since the day of the

last departure underway. As seen in Figure 18, the APAD increases as time underway increase in the shape of a log function.

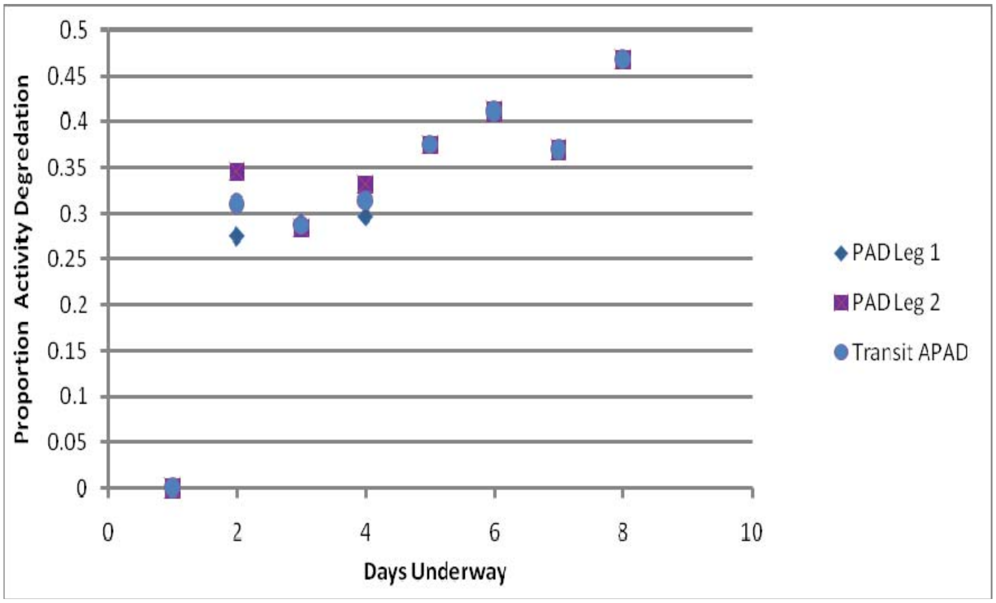


Figure 18. Proportional Activity Degradation vs. Days Underway

A standard linear regression model was formulated to model the APAD using the number of days since last in port period. In the model, y_i represents the random independent variable (APAD) for a crewmember *i*. Let $x_{i1}\ x_{i2} \ldots x_{ik}$ be the *k* independent variables for the i_{th} individual. Then the model says that

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots \beta_k x_{ik} + \varepsilon_i$$

where β_j, j=0,1,…k, are unknown variable coefficients and ε_i *for* i = 1,2,…n are random errors. Errors are assumed Normal, independent, with mean equal to zero and identical

variance σ^2. This model operates on the assumption that the crew was adapted to ship motion and the major contributor to activity degradation was Sopite syndrome. The equation for the Average Proportional Activity Degradation is:

$$\hat{y} = 0.1842\ln(x_1) + 0.0729$$

Variable	Description
x_1:	Log(DAY)- Log of the number of consecutive days underway since last period in port.

Figure 19 depicts the function on the original scale graphically. Table 5 gives the model's statistics.

Table 5. Model Statistics: Proportional Activity Degradation Model

	Value	Std. Error	T value	Pr(>|t|)
(Intercept)	0.0729	0.0480	1.5178	0.1799
Log(DAY)	0.1842	0.0324	5.6764	0.0013
Residual Standard Error		0.06038 on 6 degrees of freedom		
Multiple R^2		0.843		
F-statistic		32.22 on 1 and 6 degrees of freedom, p-value is 0.001288		

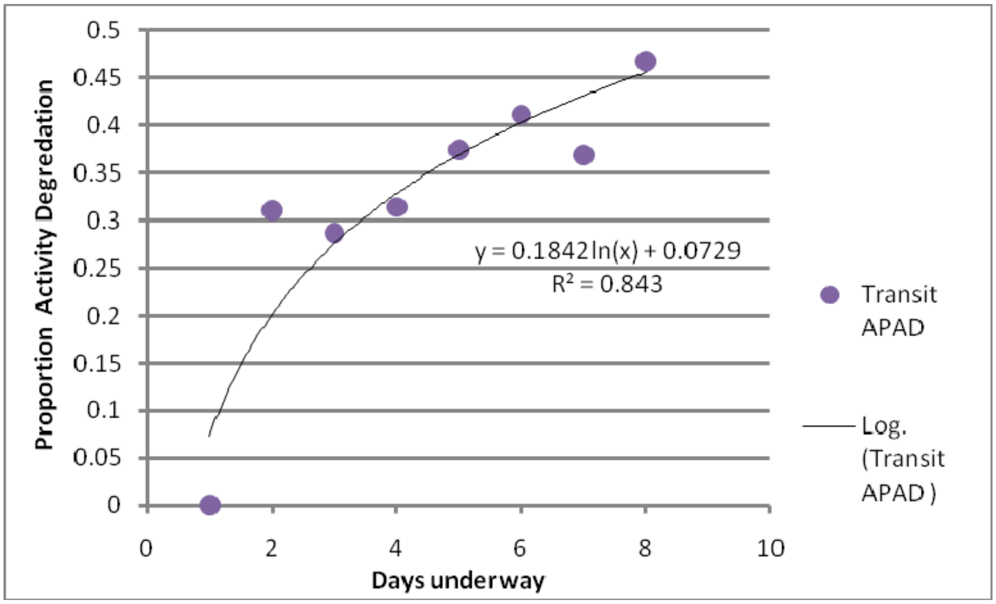


Figure 19. Average Proportional Activity Degradation vs. Days Underway

F. SOPITE MODEL RESULTS

The APAD, and thus Sopite increases as time underway increases by a log function. Due to the low resolution of the MSAQ and the small variation in MSAQ scores, it was not feasible to link MSAQ scores to activity levels. Although the MSAQ is a useful tool for periods of relatively short duration, on Sea Fighter, it is subject to the effects of environmental assimilation. The MSAQ is subjective data that depends on the participants' perceived moving average of "normal." There were instances throughout the transit when participants would complete an MSAQ indicating no symptoms, then make statements about "being tired all the time" or "just not hungry since we left port." Fatigue and loss of appetite became the new reference and participants failed to notice their gradual acceptance of the symptoms as normal. Also, the MSAQ relies on the participants' ability to recall symptoms that were felt over numerous

hours. For these reasons, it is a poor tool for identifying and reporting motion sickness symptoms for long durations. However, the Proportional Activity Degradation is an objective measure that is not susceptible to subjective reporting bias.

G. PERFORMANCE MODEL FORMULATION

Two standard linear regression models were formulated to model the time it took participants to complete the FROM and mirror tracer tasks. In the models, y_i represents the random independent variable (log(task time)) for the i_{th} individual. Let $x_{i1}\, x_{i2} \ldots x_{ik}$ be the k independent variables for the i_{th} individual. Then the model says that

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots \beta_k x_{ik} + \varepsilon_i ,$$

where β_j, $j=0,1,\ldots k$, are unknown coefficients and ε_i *for* $i = 1,2,\ldots n$ are random errors. Errors are assumed Normal, independent, with mean equal to zero and identical variance σ^2.

Due to the large number of available modeling variables, it was not initially possible to use all parameters in the models. To aid in variable selection, relationships between the variables were investigated graphically. The main relationship that was evident by graphical representation was the learning effect on the mirror tracer task. Figure 20 illustrates the steep learning effect from trial to trial associated with the mirror tracer task. Unexpectedly, as seen in Figure 21, the time to complete the mirror tracer task continually decreased for each successive trial even as wave height

increased. It appears that the learning effect dominates the time variation from trial to trial on the mirror tracer task.

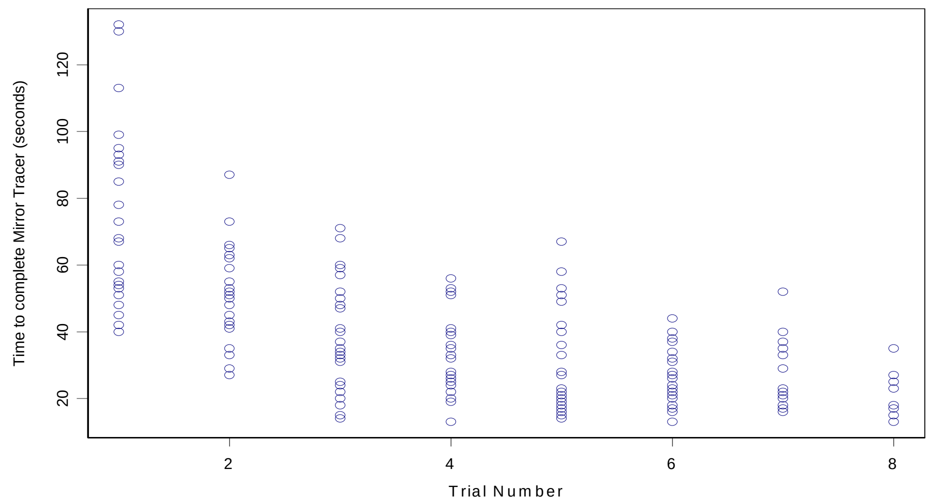


Figure 20. Time to complete Mirror Tracer vs. Trial Number

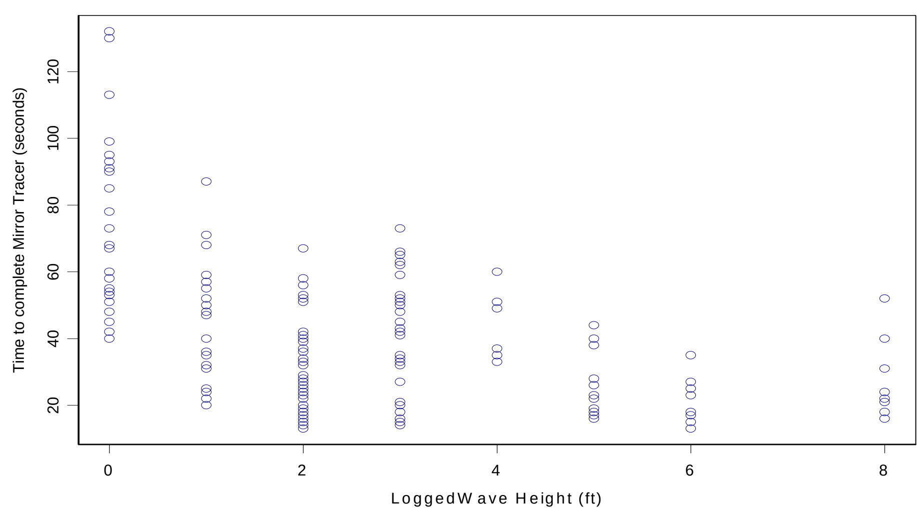


Figure 21. Time to complete Mirror Tracer vs. Logged Wave Height

Next, correlation matrices were used to investigate the relationships between variables to ensure highly correlated pairs did not over influence the model. It was found that the Gastrointestinal MSAQ, Peripheral MSAQ, Central MSAQ, Total MSAQ and MEQ2 scores were all highly correlated to one another. Total MSAQ score was selected to remain as a possible model input and MEQ2, GASTRO, PERI and CENTRAL MSAQ scores were omitted from the possible model input parameters. Once the initial possible variable selection was established, a model was built using all selected variables and two-way interactions. The Akaike Information Criterion (AIC) was used to determine which variables should be removed from the models and subsequent ANOVAs were computed to compare model iterations. Once the models were formed, specific points with large influence on the models were investigated to ensure that a small number of points with high residuals were not over-influencing the data.

1. Mirror Tracer Model

The final mirror tracer model is given by the following equation:

$$\hat{y} = 3.3004 - 0.1480 * x_1 + 0.1994 * x_2 + 0.0240 * x_3$$

Variable	Description
x_1 :	TRIAL - Individual Mirror FROM trial
x_2 :	BIG.WAVE - Binary variable, 1 if wave height > 6 ft, 0 otherwise
x_3 :	AGE - Age of participant in years

Table 6. Model Statistics: Mirror Tracer Model

	Value	Std. Error	T value	Pr(>|t|)
(Intercept)	3.3004	0.1030	32.0546	0.0000
TRIAL	-0.1480	0.0141	-10.4786	0.0000
BIG.WAVE	0.1994	0.0825	2.4164	0.0170
AGE	0.0240	0.0026	9.2322	0.0000
Residual Standard Error		0.2713 on 138 degrees of freedom		
Multiple R^2		0.6195		
Adjusted R^2		0.6112		
F-statistic		74.89 on 3 and 138 degrees of freedom, p-value is 0		

Table 6 indicates the model possesses a Multiple R^2 of .6195 and that the p-values for all variables were less than 0.05. An investigation of points with high influence reflects that the scores of one participant, the author, decreased the entire model's R^2 by four percent. The cause is due to this participant's previous experience using a mirror tracer device. Due to the familiarity with the device, the participant's scores did not improve as drastically as the other non-familiar participants. Furthermore, the participant was not a crewmember of the Sea Fighter, but was simply riding the ship. For these reasons, the author was removed from the data set for the construction of the mirror tracer model and is not reflected graphically in any mirror tracer model Figure. Figure 22 shows the leverage values for each data point. All data points with leverage values in the upper band correspond to trials during the last day of testing when

wave height was greater than six feet. Participants stated that the task was more difficult during the higher sea-state due to the increased difficulty of the cognitive processes required for the task, not MIIs caused from the ship's motion.

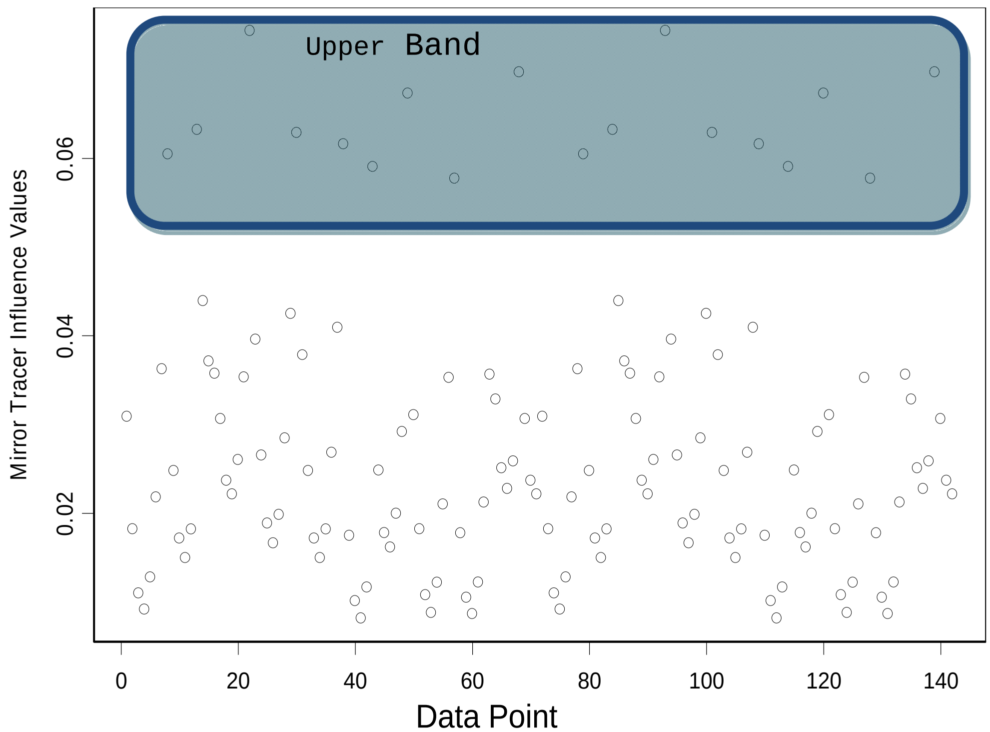


Figure 22. Mirror Tracer Model Influence vs. Data Points

Furthermore, figures 23 and 24 illustrate that the model assumption of constant variance is plausible and Figure 25 indicates that the errors (ε_i), may be assumed to follow a normal distribution.

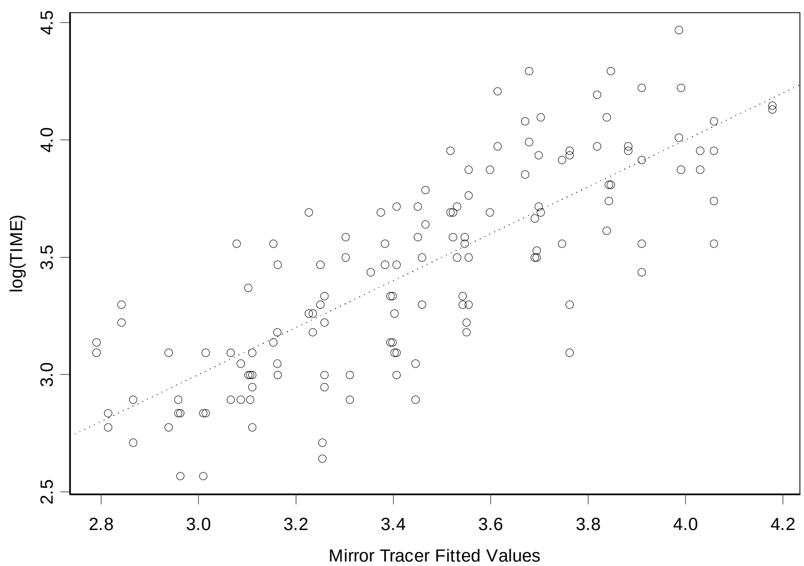


Figure 23. Mirror Tracer Actual vs. Fitted Values

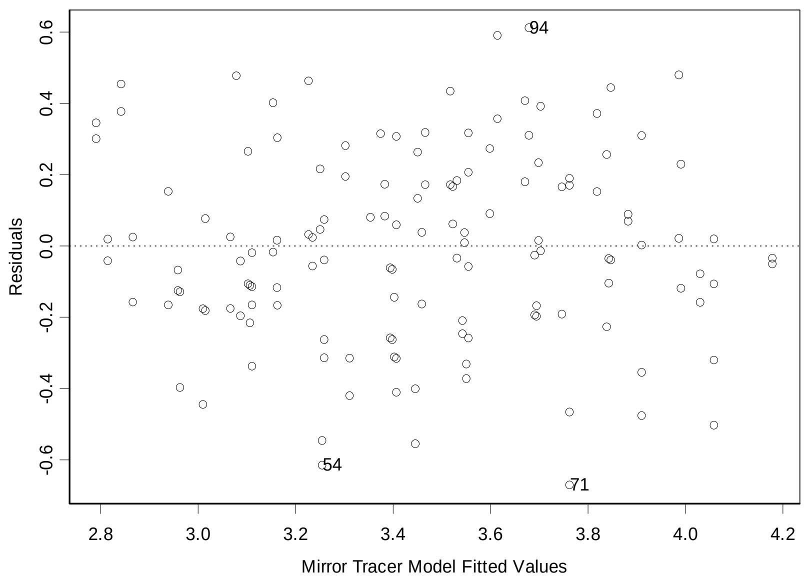


Figure 24. Mirror Tracer Residuals vs. Fitted values

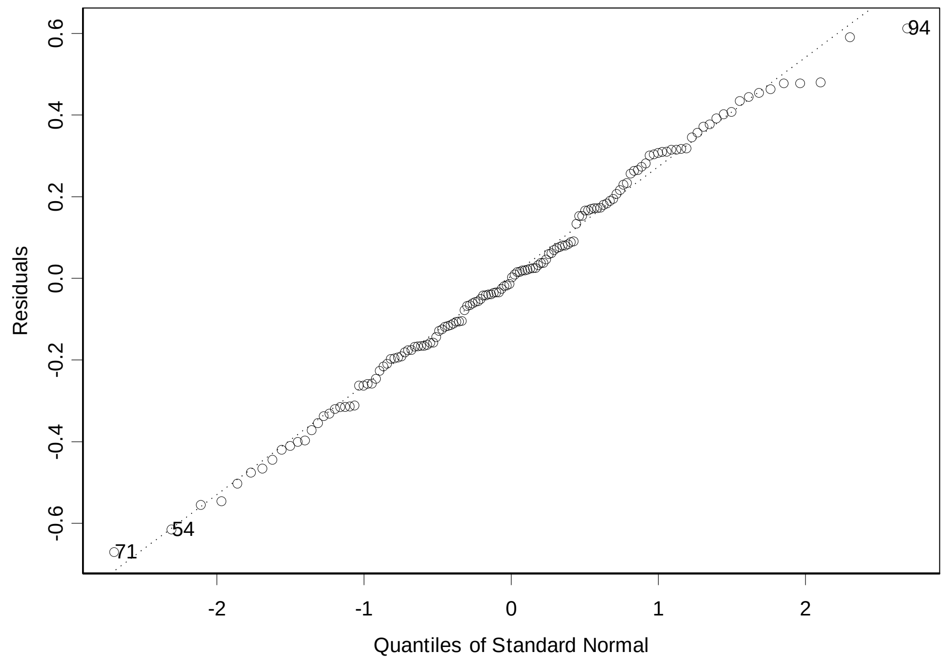


Figure 25. Mirror Tracer Normal Plot for Residuals

Additionally, Figure 26 shows residuals from the plot of l1fit(). The l1fit() method sums the absolute values of residuals rather than the square of the residuals, thus outliers have less of an effect on the model (S-PLUS® 8.0, 2007). The fact that the l1fit() residuals behave like the residuals from least-squares regression provides additional evidence that the model is free from points of high leverage and influence.

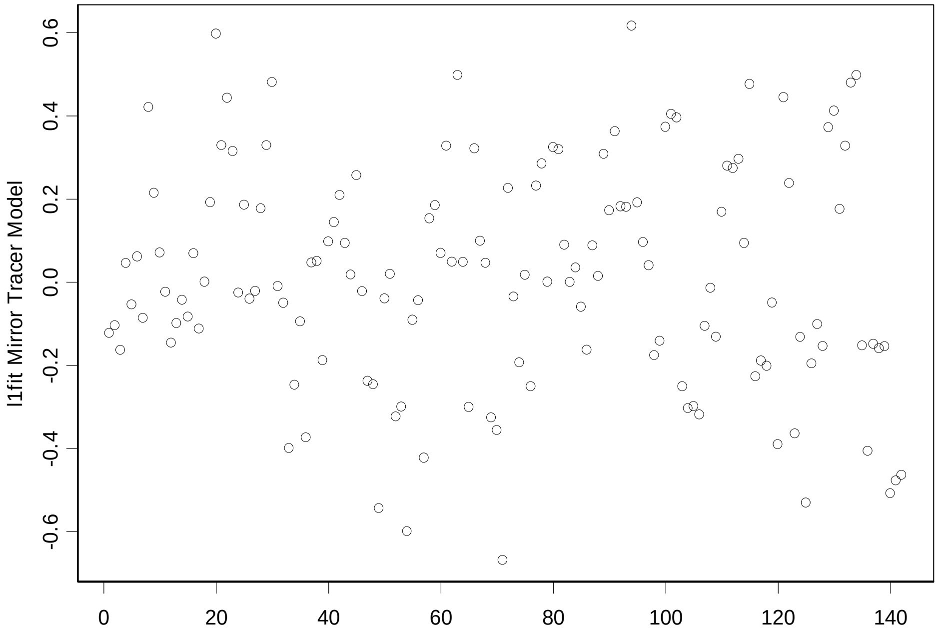


Figure 26. l1fit of Mirror Tracer Model

To ensure model robustness, the lmRobMM() method is utilized to verify appropriate variable selection. The lmRobMM() method utilizes a complex resampling algorithm, to aid in the determination of appropriate variable selection (S-PLUS® 8.0, 2007). According to the lmRobMM() method, all variables incorporated in the model belong to the model, thus giving evidence that the original model is not over-fit to the specific data set.

2. FROM Model

The final FROM model is given by the following equation:

$$\hat{y} = 5.1496 - 0.0164 * x_1 + 0.0859 * x_2 - 0.0708 * x_3 + 0.0544 * x_4 + 0.0049 * x_5$$

Variable	Description
x_1 :	TRIAL - Individual Mirror FROM trial
x_2 :	PAD - Percentage drop in activity level from day of last underway to day of test (Appendix G)
x_3 :	POSTURE - Posture of test: stand or stoop
x_4 :	DIFFICULTY - Rated difficulty of performing FROM task on that trial
x_5 :	AGE - Age of participant in years

Table 7. Model Statistics: FROM Model

	Value	Std. Error	T value	Pr(>|t|)
(Intercept)	5.1496	0.0331	155.6290	0.0000
TRIAL	-0.0164	0.0038	-4.2654	0.0000
PAD	0.0859	0.0365	2.3542	0.0199
POSTURE	-0.0708	0.0144	-4.9347	0.0000
DIFFICULTY	0.0544	0.0084	6.4604	0.0000
AGE	0.0049	0.0009	5.5260	0.0000
Residual Standard Error		0.08398 on 141 degrees of freedom		
Multiple R^2		0.4875		
Adjusted R^2		0.4693		
F-statistic		26.82 on 5 and 141 degrees of freedom, the p-value is 0		

It can be seen from Table 7 that the model has Multiple R^2 of .4875 and that the p-values for all variables

are < .05. Due to participants' poor sleep-log completion, some of the data was omitted from the model to correct missing activity scores. Figure 27 indicates that the model is subject to three high leverage points. Two of the three data points belong to the same person. The point with the highest leverage is due to a participant who scored extremely poorly on the first trial due to unfamiliarity with the testing device.

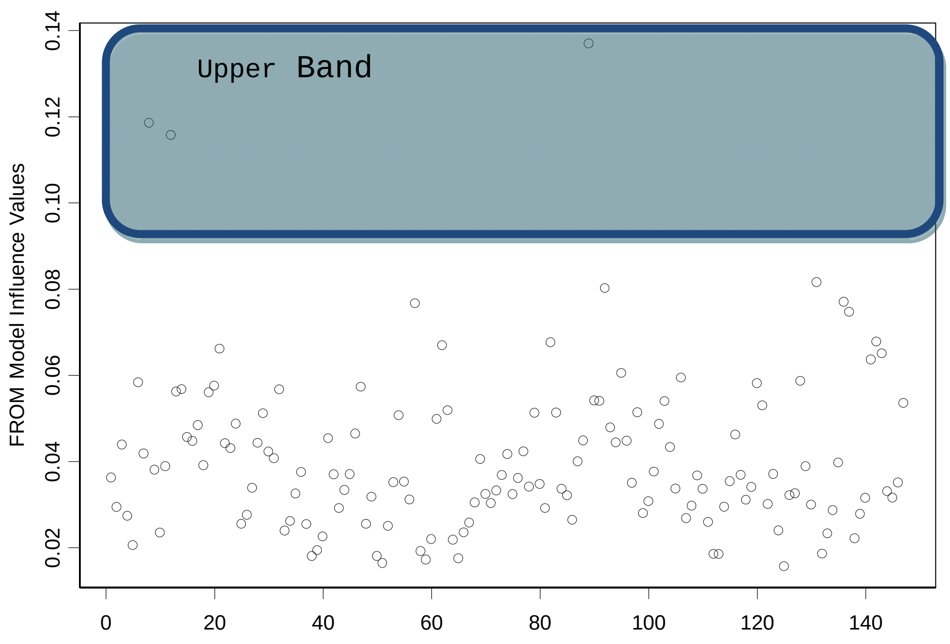
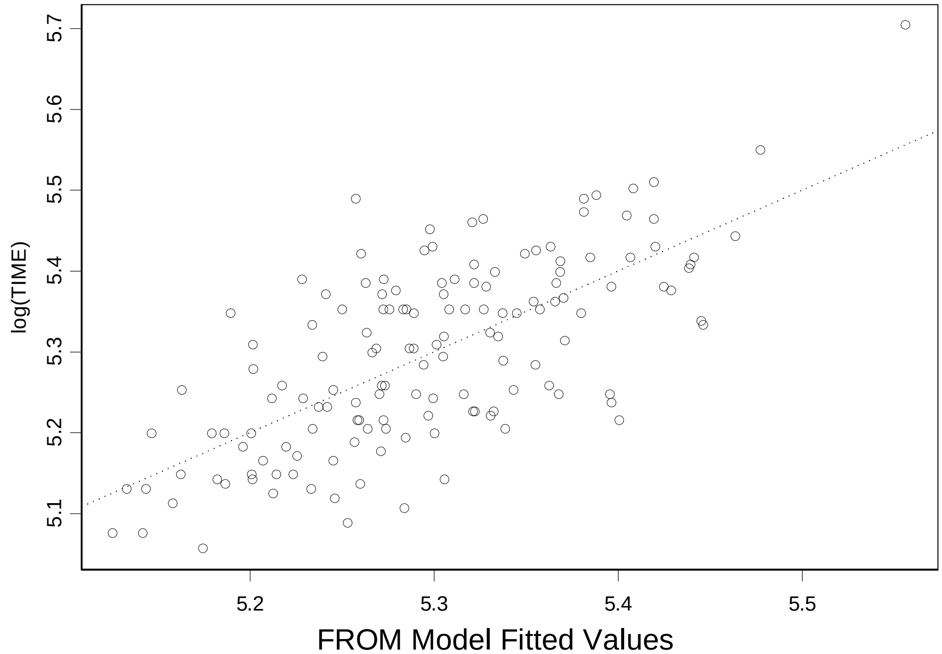


Figure 27. FROM Model Influence Values

Figures 28 and 29 show that the model assumption of constant variance was plausible while Figure 30 indicates the errors (ε_i) can be assumed to follow a Normal distribution.



FROM Model Actual vs. Fitted Values

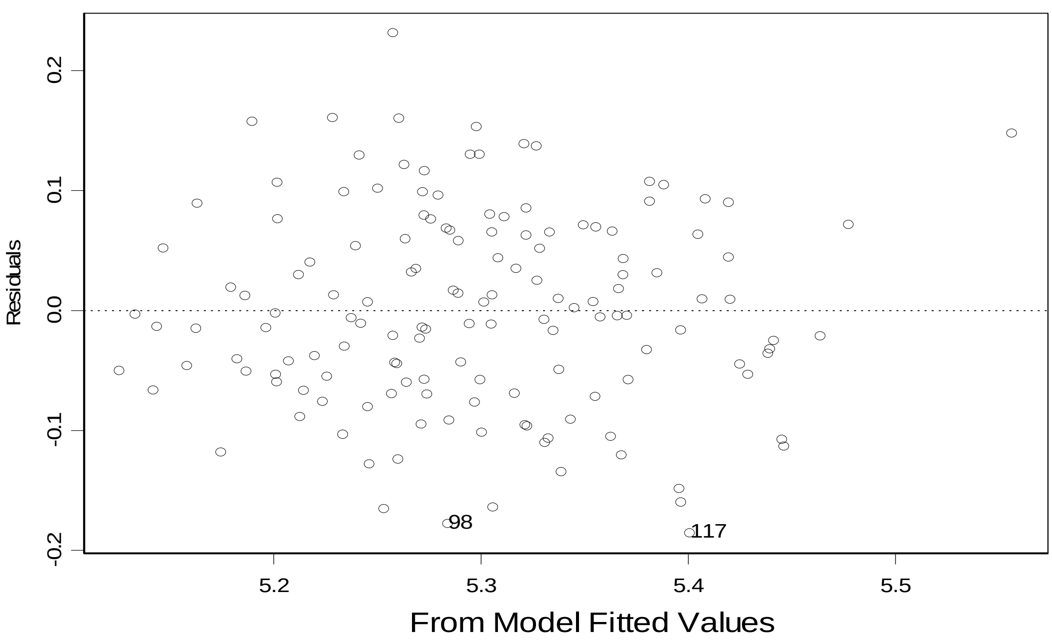


Figure 28. FROM Model Residuals vs. Fitted Values

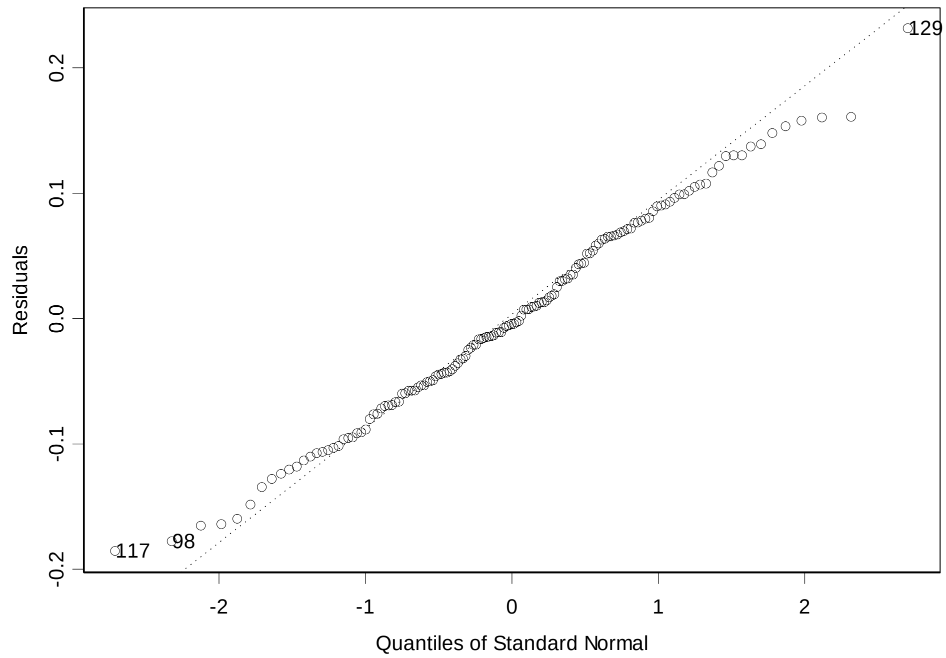


Figure 29. FROM Model Normal Plot for Residuals

H. PERFORMANCE MODEL RESULTS

1. Mirror Tracer Model Results

The Mirror Tracer Model suggests that mirror tracer completion time is dependent on trial number, age, wave height when greater than six feet, and job position on ship. Initially, wave height did not fit into the model as a continuous variable. When wave height was recoded as a binary variable representing waves greater than six feet, the variable improved the model. Throughout the transit, participants stated that the seas did not affect their performance while testing except; however, when wave height reached six feet participants experienced more difficulty with their non-dominant hand. While this effect is based on motion, there is no evidence suggested by variation in

MSAQ scores at the time of testing that the effect was based on motion sickness. The mirror tracer task could not effectively be modeled using MSAQ sub-scores or Proportional Activity Degradation. The task performance time was unaffected by Sopite perhaps because the mirror tracer took very little time and effort to complete. The resulting effect of Sopite syndrome on participant mirror tracer performance was non-existent or negligible.

2. FROM Model Results

The FROM Model suggests that the FROM completion time is dependent on trial number, Proportional Activity Degradation (PAD), posture, difficulty and participant age. For every 10% increase in Proportional Activity Degradation, there is an approximately one second increase in time to complete the FROM. Therefore, a 45% increase in Proportional Activity Degradation, corresponding to eight days underway, would be expected to result in a performance degradation of two to three percent. This dependence on Proportional Activity Degradation is expected because the task is time-consuming and requires a considerable amount of energy and concentration.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The models developed in this study are a good first approach to parametrically determining the level of Sopite related symptoms experienced by personnel embarked on a ship similar to the Sea Fighter, and the resulting performance degradation. Furthermore, wrist actigraphy-based activity measurement may be a good objective measure for Sopite syndrome on any vessel. Sopite syndrome affects different individuals in different ways. It can be seen from the models that it is also task-dependent. On the Sea Fighter, Sopite affected the crew's performance on the manual dexterity Functional Range of Motion task, but not the psychomotor mirror tracer task. It is unknown how Sopite will vary among individuals on the LCS or among the numerous tasks onboard. However, it is known that the crew will be affected and there will be tasks that are affected. This becomes increasingly more important following the implementation of reduced manning crews. Deviations in personnel performance result in larger penalties in efficiency and mission success. Reduced crew size results in a single individual's performance playing a larger role in platform capability. While the performance degradation is relatively small on a three-minute task, such a task is short in duration compared to other crucial onboard tasks that can take up to six hours or an entire on-watch period. This study gives early indications that historically accepted manning assumptions necessitate modification to include degradations caused by shipboard motion.

B. RECOMMENDATIONS FOR FUTURE STUDY

In future studies, participant selection would improve model accuracy. The study was conducted primarily on civilian contractors. While many of the contractors were once in the military, they are not active-duty sailors and may respond differently to the motion environment. Future studies should include actual active-duty personnel within Navy fitness standards. Furthermore, future study participants should more closely represent the age distribution expected to be assigned to the LCS platform. To determine effects of performance degradation in the engineering environment, future studies should include personnel from the engineering department. To ensure that activity degradation is attributed to Sopite, participants should stand the same amount of watch each day at the same times. Sleep logs should be accurately maintained to account for poor sleep quality and duration. Effort should be made to replicate a variety of likely tasks, including tasks that take extended amounts of time, aboard the LCS to determine actual personnel performance degradation.

The actigraphs used in this study were specifically manufactured for sleep analysis, but this study used them for measuring activity levels. Future studies should explore the notion of using different actigraphs more suited to measure activity levels.

Motion effects on personnel in the naval environment are categorized by countless variations. For example, the fatigue that an individual feels while on the ship could be attributed to any or all the following: Motion Induced Fatigue, Sopite syndrome, poor sleep quality due to Sopite,

sleep deprivation, melatonin levels or the increased physical strain of being on a moving platform. Although the methods by which fatigue occurs are different, the results are the same: the individual is tired. While there is value in the knowledge behind these theories, in the naval environment they may be of limited practical use. Even with the use of advanced physiological monitoring equipment, the numerous variables affecting an individual's fatigue level cannot be discriminated one from another. Rather than measuring all of the contributing variables that can make a person tired, researchers might just measure how tired they are and the resulting effect on performance. Future endeavors should focus on "chunking" theories with similar symptoms. Performance modeling can then be approached using a lumped parameter model with two or three main physiological effects.

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APPENDIX A. MEASURED PARTICIPANT DATA DESCRIPTION

Measured Participant Data	
Variable/Parameter	Description
PUMA TIME	Time in minutes a participant performed Puma Method for one day
PUMA CAL	Caloric expenditure of participant performing Puma Method for one day
TIME	Time in seconds for one trial of task with dominant hand/non-dominant hand/standing/stooping
ERRORS	Number of errors for one trial of task with dominant hand/non-dominant hand/standing/stooping
TRIAL	Specific task trial number for dominant hand/non-dominant hand/stand position/stoop position
DIFFICULTY	Rated difficulty of performing standing/stooping FROM
ACTIVITY	Activity level in Average AC/min during active periods for a given day of a given leg
MSAQ TOTAL	Calculated total MSAQ score per Figure 8
MSAQ GASTRO	Calculated Gastrointestinal MSAQ score per Figure 8
MSAQ PERI	Calculated Peripheral MSAQ score per Figure 8
MSAQ CENTRAL	Calculated Central MSAQ score per Figure 8
MSAQ SOPITE	Calculated Sopite MSAQ score per Figure 8
MEDS	Binomial variable indicating if medication was taken since last MSAQ
MEQ2	Rated motion sickness felt by participant since last MSAQ

Derived Participant Data	
PAD	Proportion of ACTIVITY decrease since last underway per Appendix G
APAD	Average Crew Proportion of ACTIVITY decrease since last underway per Appendix G

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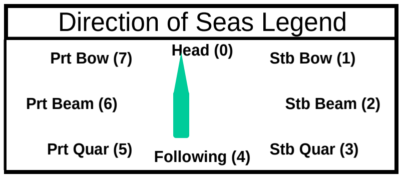
APPENDIX B. MEASURED SHIP PARAMETERS DESCRIPTION

Measured Ship Parameters	
Variable/Parameter	Description
HOURS UNDERWAY	Hours since last underway
WAVE HEIGHT	Hourly wave height in feet measured by OOD
TSK WAVE HEIGHT	Wave height in feet measured by TSK on testing days
Aw	Weighted RMS acceleration in the z direction per ISO 2631
SEAS	Relative direction of seas with respect to bow of ship
HEADING	Ships heading in degrees



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APPENDIX C. PARTICIPANT DEMOGRAPHICS DESCRIPTION

Participant Demographics	
Demographic	Description
HANDEDNESS	Binomial variable indicating handedness
AGE	Age of participant in years
SEA TIME	Participant years of time at sea
WATCH SECTION	Participant watch section
FIT	Binomial variable indicating state of fitness
ILL	Binomial variable indicating state of illness
ILL DAYS	Duration of illness in days
VERSION	Binomial variable indicating personality type of introverted or extroverted as determined by the Rotter Locus of Control scale (Appendix D)
PUMA	Binomial variable indicating participation in the Puma Method
WT	Participant weight in pounds

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APPENDIX D. ROTTER LOCUS OF CONTROL

1. a. Children get into trouble because their parents punish them too much.
   b. The trouble with most children nowadays is that their parents are too easy with them.

2. a. Many of the unhappy things in people's lives are partly due to bad luck.
   b. People's misfortunes result from the mistakes they make.

3. a. One of the major reasons why we have wars is because people don't take enough interest in politics.
   b. There will always be wars, no matter how hard people try to prevent them.

4. a. In the long run people get the respect they deserve in this world.
   b. Unfortunately, an individual's worth often passes unrecognized no matter how hard he tries.

5. a. The idea that teachers are unfair to students is nonsense.
   b. Most students don't realize the extent to which their grades are influenced by accidental happenings.

6. a. Without the right breaks one cannot be an effective leader.
   b. Capable people who fail to become leaders have not taken advantage of their opportunities.

7. a. No matter how hard you try some people just don't like you.
   b. People who can't get others to like them don't understand how to get along with others.

8. a. Heredity plays the major role in determining one's personality.
   b. It is one's experiences in life which determine what they're like.

9. a. I have often found that what is going to happen will happen.
   b. Trusting to fate has never turned out as well for me as making a decision to take a definite course of action.

10. a. In the case of the well prepared student there is rarely if ever such a thing as an unfair test.
b. Many times exam questions tend to be so unrelated to course work that studying in really useless.

11. a. Becoming a success is a matter of hard work, luck has little or nothing to do with it.
b. Getting a good job depends mainly on being in the right place at the right time.

12. a. The average citizen can have an influence in government decisions.
b. This world is run by the few people in power, and there is not much the little guy can do about it.

13. a. When I make plans, I am almost certain that I can make them work.
b. It is not always wise to plan too far ahead because many things turn out to be a matter of good or bad fortune anyhow.

14. a. There are certain people who are just no good.
b. There is some good in everybody.

15. a. In my case getting what I want has little or nothing to do with luck.
b. Many times we might just as well decide what to do by flipping a coin.

16. a. Who gets to be the boss often depends on who was lucky enough to be in the right place first.
b. Getting people to do the right thing depends upon ability, luck has little or nothing to do with it.

17. a. As far as world affairs are concerned, most of us are the victims of forces we can neither understand, nor control.
b. By taking an active part in political and social affairs the people can control world events.

18. a. Most people don't realize the extent to which their lives are controlled by accidental happenings.
b. There really is no such thing as "luck."

19. a. One should always be willing to admit mistakes.
b. It is usually best to cover up one's mistakes.

20. a. It is hard to know whether or not a person really likes you.

b. How many friends you have depends upon how nice a person you are.

21. a. In the long run the bad things that happen to us are balanced by the good ones.

b. Most misfortunes are the result of lack of ability, ignorance, laziness, or all three.

22. a. With enough effort we can wipe out political corruption.

b. It is difficult for people to have much control over the things politicians do in office.

23. a. Sometimes I can't understand how teachers arrive at the grades they give.

b. There is a direct connection between how hard 1 study and the grades I get.

24. a. A good leader expects people to decide for themselves what they should do.

b. A good leader makes it clear to everybody what their jobs are.

25. a. Many times I feel that I have little influence over the things that happen to me.

b. It is impossible for me to believe that chance or luck plays an important role in my life.

26. a. People are lonely because they don't try to be friendly.

b. There's not much use in trying too hard to please people, if they like you, they like you.

27. a. There is too much emphasis on athletics in high school.

b. Team sports are an excellent way to build character.

28. a. What happens to me is my own doing.

b. Sometimes I feel that I don't have enough control over the direction my life is taking.

29. a. Most of the time I can't understand why politicians behave the way they do.

b. In the long run, the people are responsible for bad government on a national as well as on a local level.

Note there are 6 filler items (1, 8, 14, 19, 24, 27) and 23 scoring items (Rotter’s Locus of Control, 1954).

APPENDIX E. LEG DECAY CONSTANT DETERMINATION

Indices

i	participants (1:13)
j	days of transit legs (1:8)
k	hours (1:24)
m	minutes (1:60)
g	transit legs (1:3)

Data

$ACTIVE_{ijkmg}$:	1 if active minute for person i on day j during hour k for minute m on leg g, 0 otherwise
$AC.ACTIVE_{ijkmg}$:	Activity level during active period for person i on day j during hour k for minute m on leg g
$ACTIVE.DAY_{ijg}$:	1 if $ACTIVITY_{ij}$ > 0 for person i on day j of leg g, 0 otherwise
$DAY.UNDERWAY_{jg}$:	Number of days since last underway on day j on leg g

Derived Data

$ACTIVITY_{ijg}$:	Average Activity level for person i on day j of leg g
$CREW.ACTIVITY_{jg}$:	Average activity level for all participants i on day j of leg g
$ACTIVITY.DECAY_{jg}$:	Value of computed level of crew activity for day j

$$ACTIVITY_{ijg} = \frac{\sum_{k,m} AC.ACTIVE_{ijkmg}}{\sum_{k,m} ACTIVE_{ijkmg}} \quad \forall \text{ i,j,g}$$

$$CREW.ACTIVITY_{jg} = \frac{\sum_{i} ACTIVITY_{ij}}{\sum_{i} ACTIVE.DAY_{ij}} \quad \forall \text{ j,g}$$

$$ACTIVITY.DECAY_{jg} = CREW.ACTIVITY_{1g} * DAY.UNDERWAY_{jg}^{(-DC_g)} \quad \forall \text{ j,g}$$

Variables

DC_g: Activity daily decay constant for leg g

Formulation

$$\min \sum_{j} \left| CREW.ACTIVITY_{j1} - ACTIVITY.DECAY_{j1} \right| \quad \text{(optimization for leg 1)}$$

$$\min \sum_{j} \left| CREW.ACTIVITY_{j2} - ACTIVITY.DECAY_{j2} \right| \quad \text{(optimization for leg 2)}$$

$$\min \sum_{j} \left| CREW.ACTIVITY_{j3} - ACTIVITY.DECAY_{j3} \right| \quad \text{(optimization for leg 3)}$$

s.t.

$CREW.ACTIVITY_{j1} = ACTIVITY.DECAY_{j1}$

$CREW.ACTIVITY_{j2} = ACTIVITY.DECAY_{j2}$

$-1 \leq DC_g \leq 0$

APPENDIX F. TRANSIT DECAY CONSTANT DETERMINATION

Indices

i	participants (1:13)
j	days of transit legs (1:8)
k	hours (1:24)
m	minutes (1:60)
g	transit legs (1:3)

$ACTIVE_{ijkmg}$:	1 if active minute for person i on day j during hour k for minute m on leg g, 0 otherwise
$AC.ACTIVE_{ijkmg}$:	Activity level during active period for person i on day j during hour k for minute m on leg g
$ACTIVE.DAY_{ijg}$:	1 if $ACTIVITY_{ij} > 0$ for person i on day j of leg g, 0 otherwise
$COM.DAY.UNDERWAY_{j}$:	Number of days since last underway on day j of any leg

Derived Data

$ACTIVITY_{ijg}$:	Average Activity level for person i on day j of leg g
$CREW.ACTIVITY_{jg}$:	Average activity level for all participants i on day j of leg g
$TRAN.CREW.ACTIVITY_{j}$:	Average activity level for all participants i on underway day j of any leg

TRAN.ACTIVITY.DECAY$_j$: Value of computed level of crew activity for day j

$$ACTIVITY_{ijg} = \frac{\sum_{k,m} AC.ACTIVE_{ijkmg}}{\sum_{k,m} ACTIVE_{ijkmg}} \quad \forall \text{ i,j,g}$$

$$CREW.ACTIVITY_{jg} = \frac{\sum_{i} ACTIVITY_{ij}}{\sum_{i} ACTIVE.DAY_{ij}} \quad \forall \text{ j,g}$$

$$TRAN.CREW.ACTIVITY_{j} = \frac{\sum_{g=1}^{n=2} CREW.ACTIVITY_{jg}}{2} \quad \forall \text{ j}$$

$$TRAN.ACTIVITY.DECAY_{j} = TRAN.CREW.ACTIVITY_{1} * COM.DAY.UNDERWAY_{j}^{(-TADC)} \quad \forall \text{ j}$$

Variables

TADC: Transit activity decay constant

Formulation

$$\min \sum_{j} \left| TRAN.CREW.ACTIVITY_{j} - TRAN.ACTIVITY.DECAY_{j} \right|$$

s.t.

TRAN.CREW.ACTIVITY$_j$ = *TRAN.ACTIVITY.DECAY$_j$*

$-1 \leq TADC \leq 0$

APPENDIX G. AVERAGE PROPORTIONAL ACTIVITY DEGRADATION DETERMINATION

Indices

i	participants (1:13)
j	days of transit legs (1:8)
k	hours (1:24)
m	minutes (1:60)
g	transit legs (1:3)

Data

$ACTIVE_{ijkmg}$:	1 if active minute for person i on day j during hour k for minute m on leg g, 0 otherwise
$AC.ACTIVE_{ijkmg}$:	Activity level during active period for person i on day j during hour k for minute m on leg g

Derived Data

$ACTIVITY_{ijg}$:	Average Activity level for person i on day j of leg g
PAD_{ijg}:	Proportion of Activity decrease since day of last underway for person i on day j of leg g
$APAD_{i}$:	Average Proportion of Activity decrease since day of last underway for crew day j on leg one and two

Equations:

$$ACTIVITY_{ijg} = \frac{\sum_{k,m} AC.ACTIVE_{ijkmg}}{\sum_{k,m} ACTIVE_{ijkmg}} \quad \forall \text{ i,j,g}$$

$$PAD_{ijg} = \frac{ACTIVITY_{i1g} - ACTIVITY_{ijg}}{ACTIVITY_{i1g}} \quad \forall \text{ i,j,g}$$

(where n is number of days since last underway)

$$APAD_{j} = \frac{\sum_{i,g} PAD_{ijg}}{2} \quad \forall \text{ j}$$

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